A Micro- and Macro- Analysis of Human-Machine Interfaces and Systems in Space

by

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B.S., University of Notre Dame (2016)

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Abstract

Humans and machines interact with each other on a variety of scales. Interactions can involve tightly coupled interfaces or even be socio-technical in nature. In terms of large complex systems, humans learn to interact and access these systems in the context of different social, political, technical, and economic environments. And yet despite this breadth, research on human-machine interactions on all scales depends on having metrics for evaluation and platforms upon which measurement can take place. This thesis investigated the utilization of new metrics for studying human-machine interfaces and systems at a micro and macro scale.

At the micro scale, we investigated how humans may strategize to move their bodies in order to complete a agility-based running tasks. For a slalom course, an optimal control model was formulated to analyze the characteristics of an optimal path trajectory to complete the task as quickly as possible. Opportunities to improve the model were informed by the utilization of a “micro” system - wearable inertial measurement unit (IMU) devices. While the path trajectories estimated from these devices have limitations, IMUs offer an opportunities to measure human movement in natural operational environments. In the context of space exploration, such natural environments could also include planetary surfaces with reduced gravity. To evaluate how locomotion might change in such conditions, the optimal control model was used to investigate how an optimal path trajectory would change while completing the slalom task in reduced gravity. The results demonstrated that as gravity decreased, it would take a human more time to complete the task and the curvature about turning regions would decrease (wider turns). The results and limitations of the model in nominal and reduced gravity conditions demonstrated the strong influences gravity and ground reaction forces have on the path trajectories humans can execute.

Investigating some of the limitations of the optimal models depended on having experimental trajectories estimated from the IMUs as a platform of measurement. Reflecting on how the curvature of the path trajectories decreased as gravity decreased, the metric of integrated curvature was proposed for analyzing the path trajectories of humans completing an agility task. The feasibility of using this metric was analyzed via a pilot study of another agility-based running task. Along with other common metrics of characterizing agility and path trajectories (task completion time and path length), the integrated curvature metric was evaluated using both optical motion capture (Vicon) and wearable IMU measurement platforms. The pilot study results demonstrated that subject performance in terms of completion time, path length, and integrated curvature could depend on the structure of the task and whether a subject had *a priori* knowledge of the task goal. Furthermore, the results demonstrate that there are opportunities to leverage the integrated curvature metric via the wearable IMU measurement platform to make decision-making conclusions.

Wearable IMUs offer a measurement platform that could be utilized in natural field settings, including reduced gravity planetary environments. But in order to test out and improve metrics for IMUs in these conditions, we require access to reduced gravity research platforms. Accessibility to microgravity platforms is complex and dependent on a variety of factors beyond just financial costs. And just as it is important to use human performance measurement platforms and metrics that can be leveraged in different operational environments for generalized user populations, it also important that access to microgravity research platforms is available for non-traditional partners. Non-traditional partners include users like startups, early career academics, emerging space nations, and education outreach groups.

In order to capture the complexities and nuances behind accessibility for end users in the microgravity research ecosystem, new metrics of economic openness and administrative openness were proposed. The current and future microgravity research ecosystems were surveyed using case study research methods. Systems architecture methods were utilized to analyze the stakeholders and forms of access (pathways) present in the ecosystem. Analysis demonstrated that mixed public/private pathways can foster relatively high economic and administrative openness, but these levels of openness can decrease dependent on the capabilities and type of the end user and the type of funding sources used at different stages of the pathway. Opportunities exist to refine the accessibility metrics and add new dimensions of analysis. Whether it be for wearable devices or microgravity research, by refining metrics and examining platforms now, we can help ensure accessibility to these systems for any type of user in the future.

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Chapter 1

Introduction

Quite frankly the title of this thesis, "A Micro- and Macro- Analysis of Human-Machine Interfaces and Systems in Space" may be one of the vaguest and broadest titles a reader will encounter in an engineering context. And yet, it's done on purpose. Simply put, humans and machines interact with each other on a variety of scales. Interactions can involve tightly coupled interfaces between a human and wearable device, exoskeleton, or spacesuit. But interactions can also be socio-technical in nature. In terms of large complex systems, humans learn to interact and access these systems in the context of different social, political, technical, and economic environments. Sometimes human life is dependent on these technical systems. The machines themselves can be small, like wearable devices. But they can also be the size of a football field, operate as the critical life support system, and be a symbol of international cooperation around the globe (e.g. the International Space Station). Even the spaces in which these interactions occur can vary widely, whether it be in a laboratory environment, outside in a grassy field, or even on a different planet.

And yet despite this breadth, research on human-machine interactions on all scales depends on having metrics for evaluation and platforms upon which measurement can take place. This thesis explores the development of metrics and accessibility of platforms for two very different topics. In the first half, we investigate how humans plan path trajectories in agility-based running tasks. In the second half, we examine the complex ecosystem of microgravity research and evaluate how end users gain access to research platforms.

Chapter 1 investigates how the platform of optimal control modelling can be used to investigate optimal path trajectories for humans running an agility task in varied gravity environments. As the discussion will show, some of the limitations in the model are analyzed using data collected from the measurement platform of wearable inertial measurement units (IMU) devices. Chapter 2 details the analysis of a pilot study used to investigate wearable device-based metrics. For agility-based running, the study explores a new metric to be leveraged on wearable devices and how metric values vary depending on measurement platform. Chapter 3 shifts perspective to a larger technical system, namely the microgravity research ecosystem, and proposes new metrics for end user accessibility. We ask the question, if one is not part of a large space agency or big corporation, how do you access microgravity platforms now and what dynamics will affect accessibility in the future? In order to explore this question, Chapters 4 and 5 utilize case study research and systems architecture methods to survey, analyze, and evaluate the research ecosystem. Different forms of access are identified and evaluated against the new accessibility metrics.

While broad in topics, this thesis explores how metrics can be developed and platforms can be utilized to better understand human-machine interactions within the variety of spaces humans operate in. Better understanding of these interactions can inform policy and technical system design to synergistically align with human needs and objectives.

Chapter 2

An Optimal Control Model for Assessing Human Agility Trajectories

Tightly coupled human-machine interfaces can be used to measure human performance (health monitoring wearable technology), operate a larger complex systems (piloting an aircraft or spacecraft), and improve performance (exoskeletons and spacesuits). Designing the technologies themselves requires understanding both the anthropometrics of the human population of interest and operational use cases. Operational environments are characterized by the physical dimensions of the space and how the human will strategize to move within it, the latter being much more difficult to mathematically model. Mismatches between how the technology designed to operate a system and how the human mentally determines how to operate a system can result in overall degradation in performance and sometimes injury. For tightly coupled machines like exoskeletons and spacesuits, mismatches between the technology design and human motor strategies can result in the human fighting against the exoskeleton while moving quickly on the ground or walking awkwardly in a spacesuit on a reduced gravity planetary surface. This effect could be compounded in cases where different population sets strageize differently or have different objective goals in mind to complete their tasks quickly or efficiently. This chapter investigates how optimal control theory may be used to model how humans strategize motor techniques in agility-based tasks in varied gravity environments.

2.1 Introduction

Agility can be defined as a rapid change in velocity or direction [1] and is typically measured by completion time on an agility drill. However, time based metrics alone reveal little about the underlying biomechanics contributing to performance [2–4]. Beyond completion time, there are additional measures that inform the way people complete an agility task. For example, the path trajectory selected can inform on efficiency, as estimated through path length and path curvature. An agile task performance requires selecting the appropriate trajectory and being able to perform the necessary changes in velocity to achieve the desired path. Analysis of these additional factors may lead to insights that enable individualized performance improvement.

Quantifying path efficiency includes estimating the time-varying state trajectory (i.e., position, velocity, acceleration, and jerk). The motor techniques driving these path trajectories can be a function of kinematic, dynamic, and time criteria. Previous research shows that goal oriented human motion planning of the upper extremities [5, 6] and gait locomotion [7–14] can be modelled as an optimal control problem. With the assumption that the human uses an underlying optimal control, the resulting path trajectories can be calculated, where the selected objective function drives the solution. The validity of these optimal models can be analyzed by evaluating the optimal trajectory models against experimental data [8, 9, 12]. For example, previous research shows that in upper body movements, the experimental hand trajectories of humans are similar to the minimum jerk profile (also known as maximizing smoothness) [5, 6]. Studies suggest that such optimality principles also influence lower body locomotion trajectories through the relationship between velocity, curvature, and the one-third power law [10, 11, 13, 15]; however, spatial variability was observed between subjects in comparing gross whole-body locomotion to foot step paths [14]. Recent work has also investigated the optimality principles that may influence the planning of human walking paths, evaluating objective functions such as metabolic cost [12] and movement smoothness [11, 13–15].

While there is research investigating an underlying optimal control for walking [8–10, 14], for sagital plane limb movement while treadmill running [15], and metabolic cost oriented biped models at different gait speeds [12] such a relationship has not been investigated for curved running tasks. Additionally, optimal control techniques have been shown to be inadequeate in explaining sudden avoidance behaviors [16]. In an agility-based running task, the athlete is instructed to complete a course as fast as possible. For a planned agility course, it is unclear how a human may use known waypoint locations with the goal of minimizing time to inform the underlying objective function to achieve the task. While the goal is to minimize time, it is possible that the athlete still minimizes energy to a lesser extent. As changing acceleration of the center of mass requires changing applied ground reaction force, a surrogate for reducing energy could be minimizing jerk (reducing acceleration changes). Chang and Kram [17] have shown experimentally that limitations to maximum running speed during curves are driven by the ground reaction forces necessary to attain maximum velocities compared to straight running. Thus, it is important to include the ground reaction force within the constraints to this problem formulation.

In this chapter, a planned agility task is formulated as an optimal control problem and the relationship between estimated path trajectories and the selected objective function is investigated. Specifically, the criterion of minimizing the magnitude of the squared jerk and minimizing final time was analyzed with constraints on speed, acceleration, and maximum ground reaction force that can be produced while running without slipping. The sensitivity of the solution to gravity was also investigated. The optimal control solutions are compared to experimental data, highlighting a faster and slower athlete.

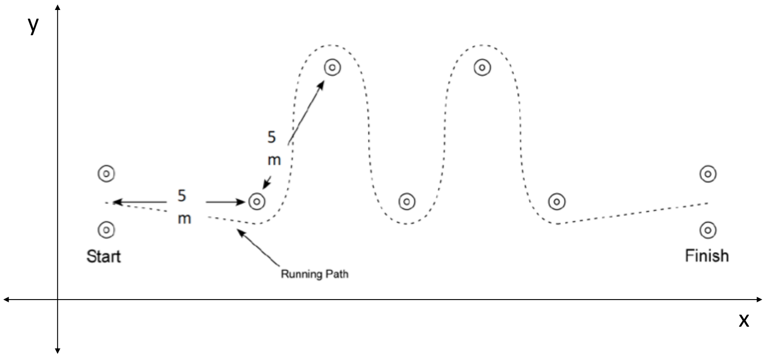


Figure 2-1: Schematic of the agility run task with coordinate system used in the analysis shown.

2.2 Methodology

2.2.1 Participants and Experimental Protocol

The present analysis used data from a previous experiment [18] in which participants performed a slalom agility run. The task examined (Fig. 2-1) requires the participant to run from the start cones to the finish cones as fast as possible, while going around the five waypoint cones without slipping. All cone markers were placed 5 meters from each other. Participants started from rest and were instructed to come to a stop at the finish.

A study was conducted with 32 recreational athletes (17M, 15F; mean (SD) age: 20.1 (2.1) years, height: 1.75 (0.13) m, mass: 71.3 (13.7) kg). The study was carried out on an outdoor lawn. The agility run was completed as an obstacle within a larger obstacle course. All participants provided informed written consent and the protocol and data analysis were approved by the University of Michigan Institutional Review Board and the Massachusetts Institute of Technology Committee on the Use of Humans as Experimental Subjects. For the current analysis, two trials are highlighted that exemplify fast and slow strategies.

Before running the course, participants donned an array of inertial measurement units (IMUs) (APDM, Portland, OR, 128 Hz sampling, +/-6G acceleration, +/-2000 deg/sec angular rate)) on the major body segments. In this analysis, the IMUs worn on each foot provide kinematic data to estimate the foot trajectories following Ojeda and Borenstein [19]. In summary, the method uses gyroscope and accelerometer data to estimate spatial orientation, and then integrates translational accelerations twice to yield foot velocities and position. Drift (and other inertial sensor) errors were reduced by applying the zero velocity update algorithm.

2.2.2 Optimal Control Formulation

An optimal control problem was defined and solved numerically using GPOPS-II [20] in Matlab (MathWorks, Natick, MA). The optimal control problem consists of the states, controls, constraints, and objective function. The agility run was expressed as a point-to-point task in Cartesian coordinates, with interior point constraints on the state variables to maintain continuity of the solution. The conditions of the problem are defined in Fig. 2-2. The accuracy tolerance for the constraints was set to 10^{-6} following standards from other examples of utilizing GPOPS-II [20] and feasibility of solution convergence.

The interior point constraints on the state variables are used to enforce the goal of navigating around the 5 waypoint cones of the slalom run and enforce continuity of the solution. The inequality constraints on velocity and acceleration were defined based on the recorded limits of human speed and acceleration [21]. The inequality constraint on the jerk control input was defined by analyzing the theoretical limits of power a human can produce while accelerating in a sprint [21]. These constraint values were supported by experimental data collected after participants completed the agility task as the values recorded experimentally were less than the inequality constraint values [18]. The ground reaction forces are a function of instantaneous velocity, tangential acceleration, and path curvature (ρ). The derivation of the ground reaction force constraint is provided in Appendix A. Equality constraints on initial and final velocity are set to zero to model a subject starting and stopping at rest. Completion time (t_f) was defined as a free variable, but was given an upper bound as per the setup required of the GPOPS-II method [20]. Completion time was initially set to 15 seconds, a few seconds longer than the slowest experimental subject [18].

States	Position Velocity Acceleration	$x(t), y(t)$ $v_x(t), v_y(t)$ $a_x(t), a_y(t)$
Control	Jerk	$j_x(t), j_y(t)$
Constraints	Continuity at Waypoints $x_1(t_1^-) = x_1(t_1^+) \dots x_5(t_5^-) = x_5(t_5^+)$ $y_1(t_1^-) = y_1(t_1^+) \dots y_5(t_5^-) = y_5(t_5^+)$ $v_{x_1}(t_1^-) = v_{x_1}(t_1^+) \dots v_{x_5}(t_5^-) = v_{x_5}(t_5^+)$ $v_{y_1}(t_1^-) = v_{y_1}(t_1^+) \dots v_{y_5}(t_5^-) = v_{y_5}(t_5^+)$ $a_{x_1}(t_1^-) = a_{x_1}(t_1^+) \dots a_{x_5}(t_5^-) = a_{x_5}(t_5^+)$ $a_{y_1}(t_1^-) = a_{y_1}(t_1^+) \dots a_{y_5}(t_5^-) = a_{y_5}(t_5^+)$ Inequality constraints on velocity, acceleration, jerk and ground reaction forces $0\frac{m}{s} \le v_x(t) \le 10\frac{m}{s}$ $-10\frac{m}{s} \le v_y(t) \le 10\frac{m}{s}$ $-10\frac{m}{s^2} \le a_x(t)\ ), a_y(t) \le 10\frac{m}{s^2}$ $-30\frac{m}{s^3} \le j_x(t), j_y(t) \le 30\frac{m}{s^3}$ $\left[\frac{dv}{dt}\right]^2 + \left[\frac{v(t)^2}{\rho}\right]^2 \le (\mu g)^2$ Start and stop at rest $v_x(0) = 0$ $v_y(0) = 0$ $v_x(t_f) = 0$ $v_y(t_f) = 0$	

Figure 2-2: Conditions of Optimal Control Problem

However, this variable was further refined for one of the optimal cases following initial analysis and the rationale is discussed in Section 2.3.1.

A multi-criterion objective function was formulated to evaluate minimizing completion time and minimizing the sum of squared jerk (Equation 2.1). Here, x represents position in the x dimension, y represents position in the y dimension (axes defined in Fig. 2-1), and t represents time. The criterion of minimizing completion time is weighted by ω and the criterion of minimizing jerk is weighted by λ. To evaluate a minimum time optimal path, λ is set to zero. To evaluate a minimum jerk optimal path, ω is set to zero. The minimum jerk criterion was derived as in Flash and Hogan [5] where an optimally smooth path is calculated by defining the objective function as minimizing the sum of the squared jerk terms. For the purposes of this chapter, only one criterion was considered at a time. The optimal trajectories presented are either minimum time trajectories or minimum jerk trajectories.

$$C = \omega t_f + \lambda \times \left[\frac{1}{2} \int_{t_0}^{t_f} \left(\left[\frac{d^3x}{dt^3} \right]^2 + \left[\frac{d^3y}{dt^3} \right]^2 \right) dt \right] \tag{2.1}$$

2.2.3 Data Analysis

To validate the GPOPS-II method, the analytical minimum jerk solution from Flash and Hogan [5] and the GPOPS-II solution were plotted against each other for the case of one waypoint. Once the GPOPS-II method was validated for the one waypoint task, the problem definition was expanded to include all five cone waypoints of the agility task, which extends from [5] and is described via the interior point constaints in Fig. 2-2 and Equation 2.1.

The full agility run problem was then successively evaluated for a minimum jerk optimal path and a minimum time optimal path. For the minimum time optimal path, the sensitivity of the model to different values of gravity and friction coefficients were evaluated. The optimal path models were then compared to the experimental trajectories run by subjects. Specifically, the path length and path curvature of an exemplary fast and slow performing participant were compared to the optimal model trajectories.

The comparative metrics were defined similarly to the methods used by Zaferiou et al. [18]. Path length was calculated by summing the Euclidean norms between each time point of the trajectories. Experimental completion times were defined by using a step size threshold to determine when the subject was stationary versus running. Turning regions were defined using a threshold of curvature as follows. For each trajectory, the peak curvature points at the five inner cones were identified. A curvature threshold was set at one half of the lowest peak curvature. The regions with curvature greater than the threshold were defined as the turning regions. The completion time for each turning region was also calculated.

2.3 Results

2.3.1 Optimal Models

The analytical and GPOPS-II solutions Fig. 2-3 highlight the similarity between the solutions for a path with a single waypoint. The root mean square error between the analytical and GPOPS-II trajectories was less than 0.15 meters. The GPOPS-II problem definition within Matlab was then expanded to include all five waypoints of the agility run task. The five waypoints of the full agility run problem correspond to the five inner cones of Fig. 2-1. The optimal paths for minimum jerk and minimum time are shown in Fig 2-4. For the minimum jerk solution Fig. 2-4a, the final time parameter was fixed to 12.71 seconds, equivalent to the completion time of the slowest subject. While the formulation of the problem has a free final time, the nature of minimizing jerk generates reduced velocities, and thus the solution is always constrained by the upper bound on the final time. The minimum time optimal path (Fig. 2-4b) generated a final time of 12.12 seconds.

In Fig 2-4, the x-axis is the starting forward direction. Participants start at the left-most cone and end at the right-most cone. Qualitatively, Fig 2-4a shows that the smoothest way to run the task involves taking a wide first turn, slower cutting turns

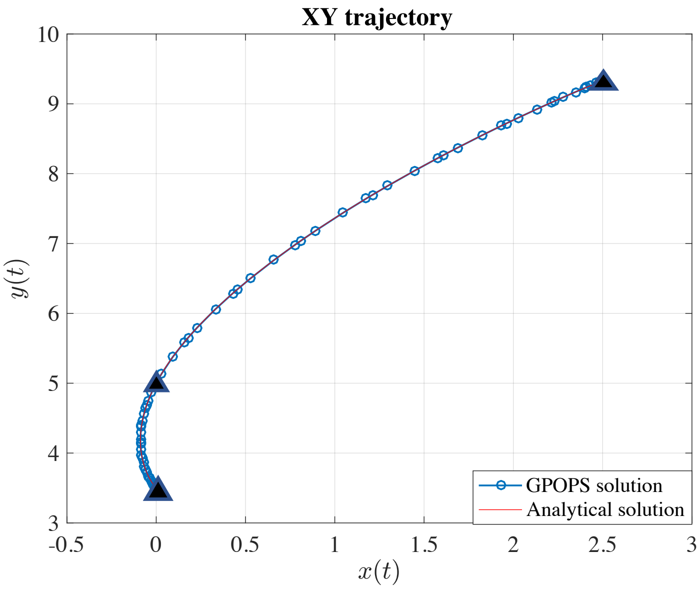
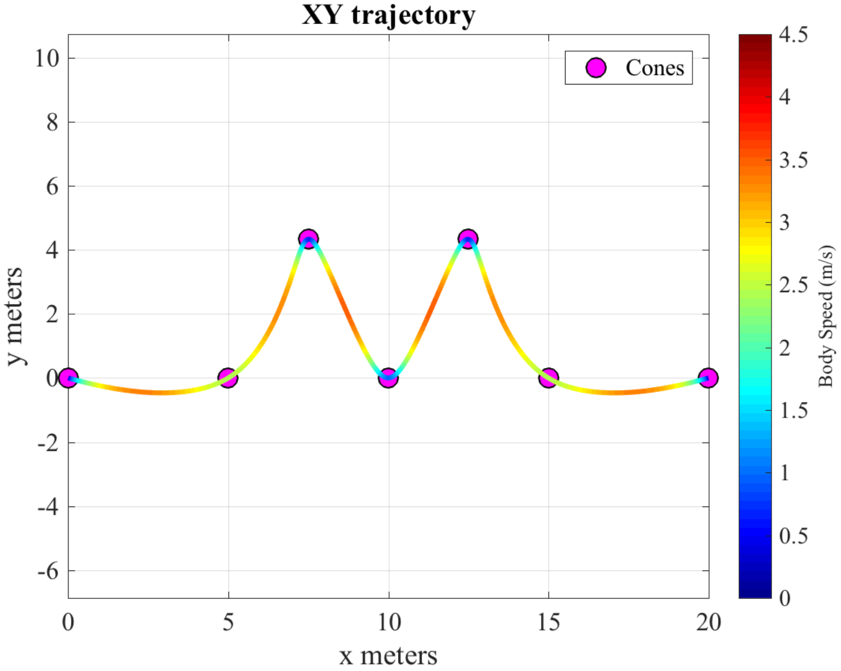


Figure 2-3: Optimal GPOPS and analytical solutions for one waypoint. Triangles represent the start, waypoint, and end locations.

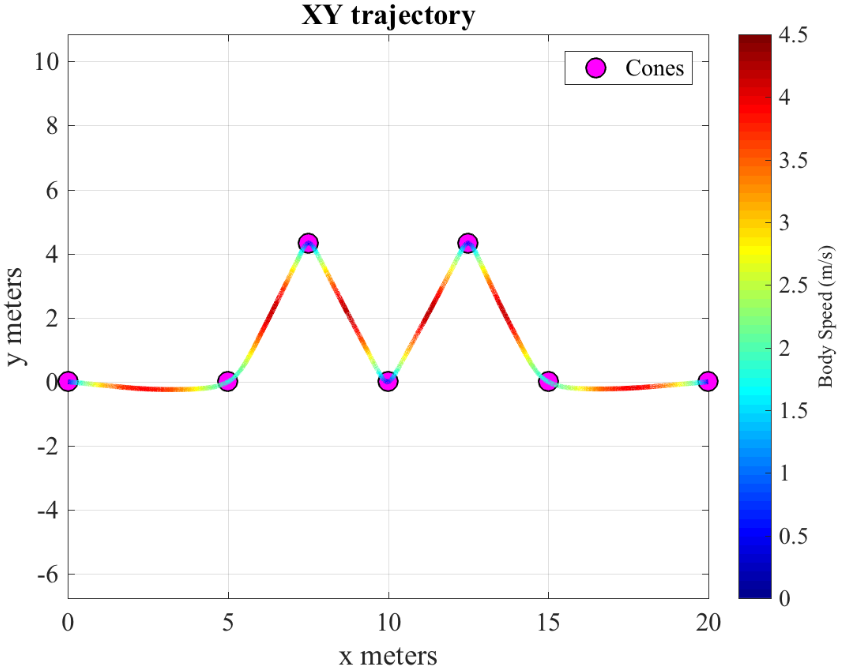
for the next three inner cones, and then finishing with another wide turn-around the last cone. In contrast, the minimum time optimal path in Fig. 2-4b involves turns with increased curvature and (zero curvature) straightaways between the turn regions. The average curvature per turn phase around the cones is shown in Table 2-6. The quantitative data support the qualitative investigation, with the minimum time trajectory having increased curvature and decreased turn time for all cones.

Parameter Sensitivity

The ground reaction force constraint is influenced by gravity and the friction coefficient of the running surface. Nominal, Martian, and lunar gravity were evaluated at $9.8\frac{m}{s^2}$, $3.71\frac{m}{s^2}$, and $1.62\frac{m}{s^2}$, respectively. The nominal static friction coefficient μ was evaluated at 0.45, equivalent to that of a natural grass rugby field [22]. Fig. 2-5 (a) and (b) presents the minimum time optimal path evaluated at Martian and lunar gravity for nominal μ, with Table 2-6 providing the quantified mean cone curvatures and turn times at each cone. Decreasing gravity decreases the mean curvature and increases time during each turn.



(a) Optimally Smooth Path



(b) Minimum Time Optimal Path

Figure 2-4: Optimal Path Trajectory Models. (a)shows the optimally smooth path evaluated with minimum jerk criterion at a fixed completion time of 12.71 seconds. (b) shows the minimum time optimal path with resulting completion time of 12.12 seconds. The color bar on the right shows the range in body speed which is overlaid on the trajectory.

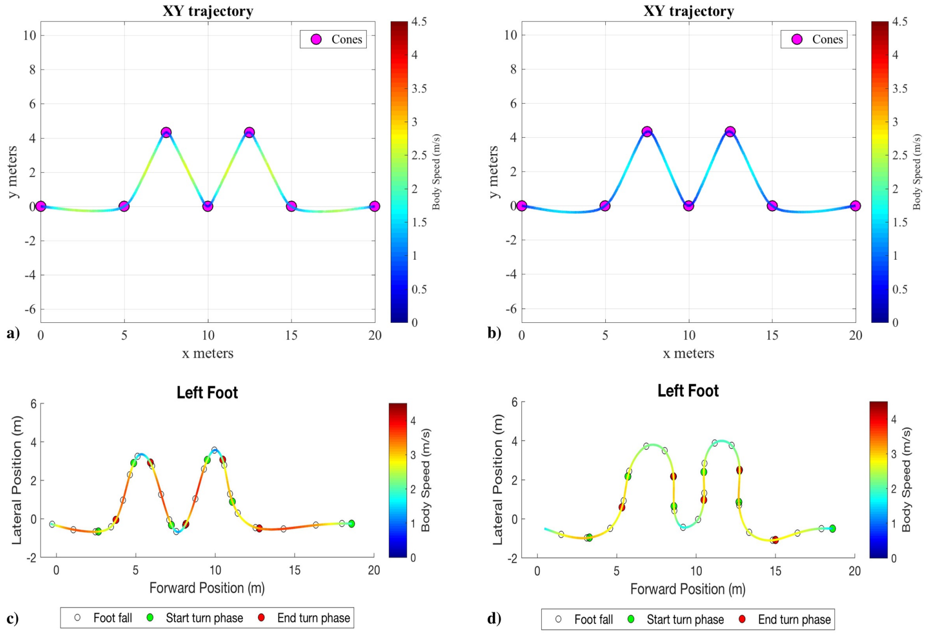


Figure 2-5: Changing Gravity and Experimental Trajectories. (a) Minimum time optimal path evaluated at $g = 3.71\frac{m}{s^2}$ and $\mu = 0.45$. (b) Minimum time optimal path evaluated at $g = 1.62\frac{m}{s^2}$ and $\mu = 0.45$. (c) Path trajectory of Subject A, who completed task in 10.70 seconds. (d) Path trajectory of Subject B, who completed task in 12.71 seconds. The color bar keys on the right of each graph show the range in body speed which is overlaid on the trajectory.

Experimental Comparison

The left foot trajectories of the fastest and slowest performers are plotted in Fig. 2-5 (c) and (d). The fastest subject completed the task from start to stop in 10.70 seconds. The slowest subject completed the task in 12.71 seconds. The path length and average curvature were averaged for both feet for each subject (Fig. 2-6). The fastest performer was able to complete the task in a faster time than the computationally estimated fastest time, with a shorter path length, but with lower curvatures. The slower performer had a longer path length, longer times during the turns, and a smaller curvature than the fast performer.

Type	Task time (sec)	Path Length (m)	Mean curvature over turn phase (1/m)					Duration of turn phase (sec)				
			Cone 1	Cone 2	Cone 3	Cone 4	Cone 5	Cone 1	Cone 2	Cone 3	Cone 4	Cone 5
Subject A	10.70	29.40	0.66	1.72	1.78	2.11	0.49	0.51	0.81	0.77	0.84	0.77
Subject B	12.71	32.08	0.40	0.61	0.87	0.75	0.47	0.98	1.92	1.71	1.89	1.33
Minimum Jerk Nominal	12.71	30.95	0.24	3.49	0.76	3.49	0.24	1.86	1.09	1.73	1.09	1.86
Minimum Time Nominal	12.12	30.29	0.73	4.97	4.01	4.84	0.74	0.54	0.62	0.65	0.63	0.53
Minimum Time $g=3.71$ m/s^2	19.68	30.38	0.71	3.61	3.58	3.07	0.71	0.88	1.12	1.11	1.17	0.88
Minimum Time $g=1.622$ m/s^2	30.31	30.29	0.59	2.23	2.29	2.26	0.60	1.49	2.10	2.11	2.11	1.51

Figure 2-6: Analysis of Optimal and Experimental Trajectories

2.4 Discussion

Analyzing the similarities and differences between the optimal and experimental path trajectories can lend insights as to how the optimal models can be improved for eventual utilization in human-machine interfaces. The results shown in Fig. 2-4 present the optimal path trajectories for the planned agility task, as defined by the conditions in Table 2-2. The minimum time trajectory solved with these conditions found a task completion time of 12.12 seconds. This value is longer than that of the fastest experimental subject, 10.70 seconds. However, the optimal model was evaluated with the inequality constraints applied throughout the entire time series. By applying the ground reaction force constraint at each point of the trajectory, the model applies the constraint during times when a human could be in flight phase during running, i.e., not in contact with the ground. As a result, the model over-restricts the ground reaction forces relative to the experiment and thus reduces the velocity that can be achieved, which increases the time estimate. While this model assumption limits the generalization to natural running, there is opportunity to improve the model in the future.

The solution to the minimum jerk optimal trajectory (Fig. 2-4a) was evaluated with a fixed task completion time constraint of 12.71 seconds, identical to the completion time of the slowest subject. When evaluating for a minimum jerk trajectory, it was found that the completion time of the task would always be equal to the upper bound of completion time defined within the GPOPS-II formulation. As jerk is defined as the third derivative of position, it follows that to minimize jerk across the optimal trajectory, lower completion times increase jerk overall. Thus, minimizing jerk is directly opposed to the stated goals for participants to minimize time.

The optimal path trajectory was also evaluated for its sensitivity to changing gravity, although results must be interpreted with caution as reduced gravity also affects the time in contact with the ground. Adjusting the gravity parameter for the minimum time optimal trajectories, affected task completion time and average curvature about turns of the inner cones. As shown in Table 2-6, when friction was kept constant and the value of the gravity parameter decreased, the completion time increased and average curvature about the inner three cones decreased. The gravity term bounded the ground reaction force constraint, which affects the accelerations a human could produce while turning without slipping. As the ground reaction force constraints narrowed the feasible solution space with decreasing gravity, the optimal trajectories result in longer completion times and smaller curvatures. Average curvature about the inner turns decreased, modelling that a human would be unable to make tight turns under these conditions. The optimal trajectories and results in Table 2-6 suggest that if a human were to attempt the agility run task in Martian or lunar gravity, the subject would be limited in their ability to make quick changes in direction and their task completion time would be longer than that in Earth conditions. These trends are anecdotally supported by those training in reduced gravity simulators. Users of the NASA Active Response Gravity Offload System (ARGOS) suggest that different turn strategies exist, such as creating a torque when leaving the ground such that a rotation occurs while in the flight stage. De Witt and Ploutz-Snyder [23] have also shown that for a given running speed in microgravity, ground reaction forces were lower than in 1G with current gravity-replacement forces, which has implications for turning ability.

A comparison of recreational athlete performance on this agility run task was highlighted (Fig 2-5 (c-d), Table 2-6). The trajectories of the fastest subject (Subject A, 10.70 seconds) and the slowest subject (Subject B, 12.71 seconds) were shown. Although the experimental path lengths should be at least 30 meters, due to the course geometry in Fig 2-1, the estimated path length of Subject A was slightly less at 29.40 meters, as shown in Table 2-6. This difference in path length may be due to several contributing factors. Saturation of the IMU accelerometer signal may have caused a loss of accelerometer-derived displacement, thereby underestimating path length, or a component of the path length may not have been estimated correctly in the horizontal plane due to possible inaccuracies in the orientation estimation. Alternatively, there may be contributing factors due to the experimental setup: small errors in the cone placement, or if the first running footfall was made by the left foot and the last footfall made by the right foot.

Qualitatively there are differences in the path trajectories of Subject A and B, specifically in the optimal speed throughout the trajectory. Subject A, the high performer, selected a strategy with higher average curvature around each cone turn. In comparison to the optimal trajectories, the subject trajectories differ most in average curvature over each turn and the selected speed throughout the trajectory. Subject A presents a speed pattern similar to that of both optimal trajectories by maintaining high speed in the straightaways between cones and with rapid deceleration while approaching each cone. Both subject trajectories show lower average curvature per turn than all variants of the optimal trajectories. This lower curvature points to the importance of extending the model to have the flight phase modeled separately from the stance phase. Additionally, the footfalls measured experimentally needed to make contact with the ground exterior to the cones, which could limit the upper bound of the experimental curvature when compared to the optimal trajectories. The interior point constraints of the optimal model simply used the cone positions and the resulting trajectories were very tightly located to the cones (purple markers in Fig. 2-4). The experimental trajectories (Fig. 2-5) suggest that it may not be physically feasible to place one's foot that close to a cone while running.

The experimental trajectories presented were of each participants' left footpath, with Table 2-6 presenting values averaged between feet. As highlighted by Chang and Kram [17], the inner and outer feet impart different peak forces. Thus, future modeling efforts may want to consider the feet independently. The present model considered the person as a point mass moving along a trajectory. Different insights of human path planning may be gained by specifically examining how the individual foot trajectories compare to the trajectory of the center of mass. While this model allowed the center of mass to cross directly above the cone locations, the center of mass of high performers may tip interior to the cones (despite the foot trajectories remaining exterior to the cones).

The minimum jerk trajectory was evaluated at a fixed completion time equivalent to the completion time of Subject B. In terms of the curvature of the turns around the first and last cones, the Subject B trajectory is more similar to the minimum jerk optimal path than the minimum time optimal path. However, as Table 2-6 shows, Subject B's trajectory is dissimilar to the minimum jerk optimal trajectory in path length and average curvature. Subject B did not achieve a path to maximize path smoothness, with subject balancing underlying constraints of the problem in a different manner than Subject A. As task technique was self-selected by these participants, it is unclear if Subject B could have achieved improved performance with prior athletic training using the technique of long and fast straightaways.

Future work could consider expanding the experimental trajectory analysis to evaluate the trajectories of subjects' sacrum. In planning locomotion through the agility run task, it is possible that subjects prioritize their sacral trajectories, as representative of their center of mass, different than foot path trajectories. This hypothesis is further investigated in Chapter 3. Future work could also include utilizing Equation 2.1 to evaluate the agility run task via a multiple criterion objective function, by varying the weightings between the minimum time and minimum jerk criterion to produce a Pareto front. Further evaluation of the experimental dataset could be used to map the performance of the subjects to the Pareto front and respective optimal trajectories. By comparing the trajectories of high performing subjects to optimal trajectories, insights can be gained into which aspects of high performing subjects' trajectories contributed to higher performance. Paying particular attention to the path trajectory itself, and not just completion time, can contribute to understanding human locomotion planning in running tasks like the agility run.

2.5 Conclusion

In this chapter, a planned agility task was formulated as an optimal control problem and the relationship between estimated path trajectories and the selected objective function was investigated. The optimal trajectories show that it is possible to formulate the agility task as an optimal control problem. However, preliminary analysis of subject experimental trajectories suggests that the current formulation of the agility run task is limited when compared to foot trajectories. With these limitations, the model shows that locomotion would be limited in reduced gravity conditions, especially in tasks requiring sharp turns. These model results are supported by reduced gravity training. Opportunities for improving the modelling of the optimal trajectories include incorporating a dynamics model to accurately evaluate the ground reaction forces present at each footfall. Including subject specific anthropometrics in such a model can also enable subject-specific solutions to inform strategy, such as subject stride length and foot orientation.

While there are opportunities to improve the model, the results indicate that one of the primary drivers of the optimal solution is the ground reaction constraint. Such a gravity dependent solution has implications for future human exploration of reduced gravity environments. Interpreting optimal human movement trajectories at the micro scale can inform how larger wearable systems, like a spacesuit, should be designed to not impede locomotion on different planetary surfaces. By improving human movement models that highlight the the sensitivity of human movement to gravity, motion strategies could be developed that create a more informed understanding of how humans move in these different environments.

Chapter 3

Comparison of Measurement Platforms for Agility-based Motion Path Trajectories Analysis

The previous chapter demonstrated that opportunities exist to model how humans strategize completing an agility-based running task. Evaluating the performance and limitations of the model depended on the availability of experimental trajectories that were measured using wearable technology in an outdoor environment. This chapter investigates how different platforms (motion capture systems and wearable technology) could be used evaluate performance metrics and motion strategies for an agility-based running task on the ground. For human performance research on microgravity research platforms (further described in Section 4.4), motion capture systems are difficult to implement. Improving metrics that can be used with wearable technology measurement platforms can not only enable these devices to be used more appropriately in microgravity research environments, but also increase the availability of experimental data sets for comparison against optimal trajectory models.

3.1 Background

As discussed in Chapter 2, agility can generally be defined as a person's ability to rapidly change velocity or direction in response to a stimulus [1]. While measurement of agility is often experimentally limited to completion time [2–4], other measures of path performance, such as the path curvature metric used in the previous chapter, can also be examined. Literature focuses on two types of agility – planned and reactive agility. Planned agility refers to the physical action of changing direction and is evaluated by navigating a pre-defined path (similar to the task discussed in Chapter 1). Reactive agility incorporates a cognitive component by involving perception and reaction to a cue signaling turn direction [24]. Analyzing how human subjects plan and execute path trajectories, dependent on their knowledge of the goal, presents the opportunity to develop reactive agility performance measures that inform on the level of the cognitive component.

To measure positional path trajectories, motion capture systems (such as Vicon cameras) are often utilized. While highly precise, such systems are also bulky, expensive and limited to laboratory testing environments. Wearable technology systems, such as inertial measurement units (IMUs), offer the potential to extend human performance analyses into more naturalistic environments. However, the positional data obtained from wearable devices can be subject to drift error due to device limitations. One method for mitigating position drift is to perform zero velocity updates (e.g., Ojeda and Borenstein [19]). However, the presence of positional drift errors are more likely to occur within reactive agility tasks due to stutter-stepping and saturation of the accelerometer from high velocity foot strikes. The previous chapter also discussed the possibility that human subjects may prioritize optimizing sacral trajectories, as representative of the center of mass, different than foot trajectories. However, estimation of sacral positional trajectories cannot utilize the zero velocity foot update from Ojeda and Borenstein's algorithm [19]. Acknowledging that in reactive agility tasks, the complete task goals are not known *a priori*, it is also possible that subjects will strategize their trajectories differently for planned or reactive agility tasks. This chapter presents the results of a pilot study analyzing the relationship between the feet and sacrum path trajectories with planned and reactive agility performance using optical motion capture and wearable device measurement platforms. Results are also evaluated for feasibility of a proposed curvature metric on different measurement platforms.

3.1.1 Hypothesis

Subject performance in the pilot study is analyzed using the metrics of completion time, path length, and integrated curvature. Completion time is utilized since one of the goals of the agility run task used in the study is to complete the task as quickly as possible. To evaluate the path trajectories subjects execute, the metrics of path length and integrated curvature are used. Path length is used to investigate if that aspect of the path trajectory contributes to path efficiency and/or task performance. The formulation of integrated curvature is further described in the methodology. This metric is proposed and evaluated on whether it can represent the curvature profile of the trajectories, regardless of measurement platform. This pilot study hypothesized that based on Vicon optical motion capture analysis (1) trial type (planned vs. reactive) contributes significantly to task completion time, integrated curvature and path length; and, (2) path lengths differ between the feet and sacrum of a subject. In comparing Vicon-based trajectories against IMU-based positional trajectory analysis, it is hypothesized that (3) while IMU-based position estimates are still subject to drift error, the curvature profile of the IMU-based estimates are not significantly different from the curvature profile of the Vicon-based estimates.

3.2 Methodology

3.2.1 Participants

Two male adults with a military background completed the agility-based running task described in Section 3.2.2. This task is different than the task discussed in

Table 3.1: Subject Anthropometrics

Age	Sex	Height (cm)	Weight (kg)	*Greater trochanter* to ground (cm)	Knee to ground (cm)	Dominant Foot	Dominant Hand
23	Male	172.72	70.31	101	57	Right	Left
24	Male	174.26	74.03	90	50	Right	Right

Chapter 2 to enable the investigation of planned and reactive agility on the same course layout. Anthropometrics are listed in Table 3.1. Subjects were recruited from the MIT community. Subjects were eligible for participation in the study if they (1) were between the ages of 18-40 and (2) exercised at least 120 minutes per a week. Subjects were excluded from the study if they self-report (1) a history of previous lower extremity surgery, (2) lower extremity injury preventing more than three weeks of participation in physical activity in the last 6 months, or (3) any physical, cognitive or other condition that would impair their ability to perform this study's tasks or cause them to be at increased risk for injury. Procedures were approved by the MIT Committee on the Use of Humans as Experimental Subjects and subjects provided written consent.

3.2.2 Experimental Protocol

The pilot study was conducted within an indoor motion capture space utilizing twenty-two Vicon motion capture cameras. Data was captured at 100 Hz. Opal (APDM, Portland, OR) inertial measurement units (IMUs) were placed on each foot using an elastic velcro strap and on the sacrum using a tightly worn belt. Device specifications of the IMUs can be found in Appendix B. A triad of reflective markers were placed on top of each IMU using a custom designed marker plate (Appendix B). Complete marker and IMU placement on the body is shown in Fig. 3-1. On each shoe, markers were placed on the heel and near the big toe and fifth toe. Four markers were placed near the right and left anterior superior iliac spine (RASI and

LASI), and the right and left posterior superior iliac spine (RPSI and LPSI) along the sacrum belt. Four markers were placed across the head. Subjects were instructed to wear their own athletic shoes and clothing on testing days, with a compression style athletic shirt if possible.

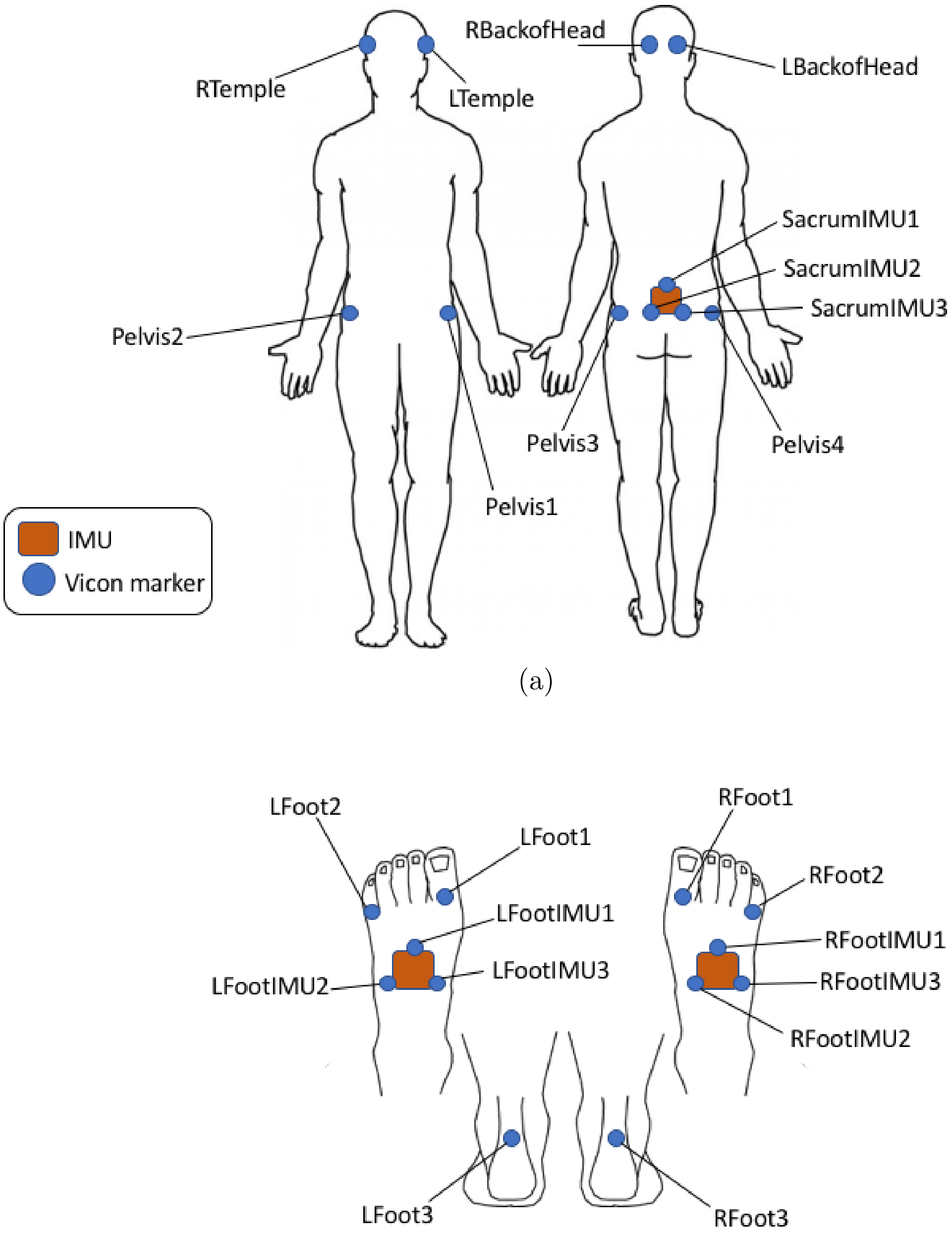
Subjects completed a five-cone agility drill, in which 5.72 cm tall circular cones were placed four meters apart, and were instructed to complete the course shown in Figure 3-2 as quickly as possible without slipping. The course was adapted from the Stop'n'Go reactive-agility test developed by Sekulic et al. [25]. Beginning at the start cones, subjects were told to run around the waypoint cone to the directed endpoint cone, touch the endpoint cone and then return back to the start cone. For planned agility, subjects were told which endpoint to touch prior to beginning the task. For reactive agility, a verbal cue was provided as the subjects passed the cue location 1.4 meters prior to reaching the waypoint cone. Subjects ran to each of the four endpoint cones five times for each trial type, resulting in 20 trials for planned agility and 20 trials for reactive agility. The test matrix is shown in Table 3.2. One subject was assigned to complete the planned agility trials first while the other subject was assigned to complete the reactive agility trials first.

Table 3.2: Subject Test Matrix

Trial Type	Endpoint Cone Order
Planned	4, 4, 1, 3, 3, 1, 1, 4, 2, 1, 3, 3, 2, 2, 4, 4, 2, 2, 1, 3
Reactive	1, 2, 1, 3, 2, 2, 4, 4, 3, 1, 2, 4, 3, 3, 4, 3, 1, 2, 4, 1

3.2.3 Metrics

During analysis of the collected data, a trial was defined as the forward path trajectory from the start cones to the point either of the feet reached within a 0.85 meter margin around endpoint cone, as measured by the position of the heel markers. This bounding box was identified in post-processing of the data in order to standardize the



(a)

(b)

Figure 3-1: Vicon Marker and IMU Placements Across Body. Squares represent IMUs that were attached using a Velcro strap. Circles represent Vicon markers with their respective labels. (a) Pelvis and Head Marker and IMU Placements. (b) Feet Marker and IMU Placements

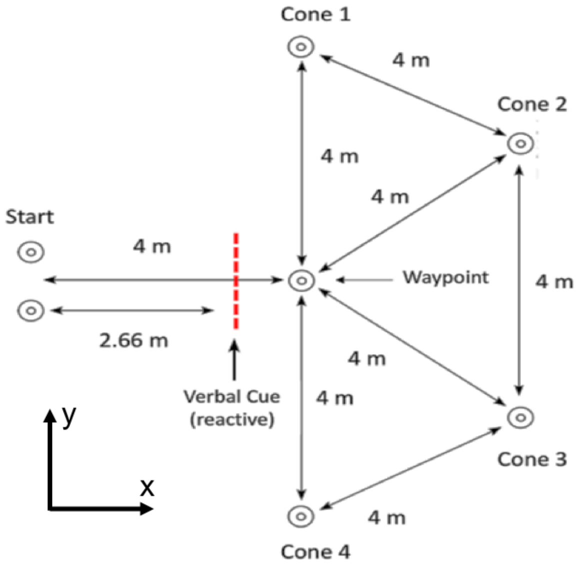


Figure 3-2: Agility Run Course Layout. The x-axis represents the forward projection of subjects as they completed the course. Cones 1 and 4 required 90° turns while Cones 2 and 3 required 60° turns

end positions for each trial and reduce the effects of marker occulsion as subjects bent down to touch the endpoint cone. Positional data captured from the Vicon markers were analyzed for the following metrics: task completion time, integrated curvature, and path length. Integrated curvatures were calculated for the sacral path trajectories measured from the Vicon markers. Path lengths were also calculated for the sacral and feet path trajectories as measured from the Vicon markers. Path length and integrated curvature were calculated for the sacrum and feet. For the IMUs, integrated curvature of the feet were calculated using positional estimates produced from Ojeda and Borenstein's algorithm [19]. The metric definitions are as follows:

Task completion time (sec) = time to complete forward path trajectory from start to a 0.85 meter boundary from the endpoint cone.

Integrated curvature (1/meters) $= \int_{t_i}^{t_n} \kappa(\mathrm{t})\,\mathrm{d}t$

where $\kappa(t) = \frac{x'(t)y''(t) - y'(t)x''(t)}{[x'(t)^2 + y'(t)^2]^{\frac{3}{2}}}$ and the integral was calculated using trapezoidal numerical integration via Matlab's *trapz* function.

Path length (meters) $= \sum_{i=1}^{n-1} \sqrt{dx_i^2 + dy_i^2}$

where $dx_i = x_{i+1} - x_i; \quad dy_i = y_{i+1} - y_i$ for each sampled point in the forward path trajectory.

In evaluating the curvature profiles for the Vicon vs IMU comparisons, $\kappa(t)$, or the instantaneous curvature [26], was utilized. The Vicon and IMU trajectories were also compared after being "smoothed" to varying degrees. In analysis of the Vicon positional trajectories, small sharp curves were present in the portions of the trajectory where foot contacts were estimated to have occurred. These small sharp curves in the Vicon and IMU trajectories were smoothed out by calculated the cubic smoothing spline via Matlab's *csaps* function [27]. This method has been used in previous analysis of agility running drills by Zaferiou, et al. [18]. These smoothed positional trajectories were then also evaluated for the integrated curvature metric.

3.2.4 Data Processing

Vicon Data Processing

The Vicon motion capture system recorded positional coordinates of the reflective markers at 100 Hz. Over the course of a trial, markers occasionally became occluded from view of the cameras due to the body position of a subject. Such gaps in positional data were filled in post-processing using the spline, cyclic, pattern and rigid body fill techniques of the Vicon Nexus software. Most gaps filled using these techniques were of a length less than 10 frames. Any gaps larger than this length were only filled if they were at the initial portion of a trial when the subject was standing stationary. The heel markers were selected to represent the position of each foot as the markers placed on the IMU marker plates often became occluded from camera view during the swing and flight phases of running. The centroid of the three Sacrum IMU markers was evaluated and utilized to represent the position of the sacrum. Raw positional data captured from Vicon were filtered using a low pass 6^{th} order Butterworth filter with a cutoff frequency of 30 Hz. The full raw data set recorded subjects' forward and return trajectories as they ran to each endpoint cone and back to start. Trial data was parsed for metric analysis by identifying when either of the heel markers were within a 0.85 meter margin around the endpoint cone and marking that point as the end of the forward path trajectory. Filtering and metric evaluations utilized custom Matlab software. The code used for evaluating metrics is included in Appendix C.

IMU Data Processing

As referenced in Appendix A, the IMUs capture raw accelerometer data, from which velocity and positional displacement can be estimated by using numerical integration. However, such estimations are subject to drift error in which small errors in acceleration measurements are compounded with each level of integration. To address drift error, zero velocity foot updates were implemented using an algorithm developed by Ojeda and Borenstein [19]. Through this method, positional foot trajectories were estimated from the foot mounted IMUs. Positional trajectory estimates were not evaluated from the sacrum IMU. Since the IMU data was collected at 128 Hz and the Vicon data was collected at 100 Hz, the IMU position data was downsampled to 100 Hz using Matlab's *resample* function to simplify further analysis. The IMU trial data was then parsed from the full raw data set using the same trial start and end indices that were used for the Vicon trial data.

The positional trajectories estimated from the IMUs require a global reference frame to be contextually interpreted. For example the positional trajectory for the left foot IMU would not be in the same general orientation as that of the right foot IMU or the Vicon-based positional trajectories. To match the orientations of each foot against each other and to the Vicon positional trajectories, the IMU trajectories were translated to originate at the same coordinates of the Vicon trajectories and then rotated about this start position. The angle of rotation was calculated by identifying the location of the first foot contact after the subject began running, calculating the angle from this location with respect to the x-axis in the X-Y plane, and finding the difference between such angles for the Vicon trajectory and IMU trajectory. Cal-

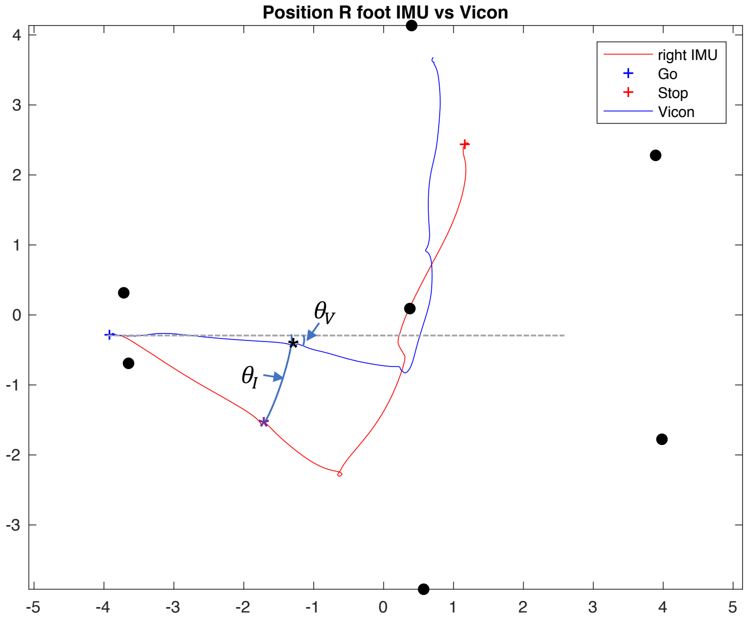


Figure 3-3: Rotation of IMU positional trajectories. Vicon positional trajectory of a right foot planned agility trial to cone 1 is shown in blue. The IMU positional trajectory of that same foot is shown in red. The IMU trajectory has already been translated to originate at the same location the Vicon trajectory begins. The asterisks represent the first identified foot contact. θ_V was calculated with respect to the beginning of the trajectory, the black asterisk, and the x-axis. θ_I was calculated with respect to the beginning of the trajectory, the purple asterisk, and the x-axis. The IMU trajectory was then rotated counter-clockwise by the difference between θ_V and θ_I.

culating the angle of rotation is visualized in Fig. 3-3. The first foot contact was identified by analyzing the vertical z position of the heel marker. The first minima in the z-direction, or the point at which the first heel-off event occurred, was used as the first foot contact. Since this event was early on in the trial, it's location estimate is less likely to have been affected by drift error.

3.2.5 Statistical Analysis

Evaluation of Hypotheses (1) and (2)

Based on Vicon marker data, separate multifactor analysis of variance models were fit for the dependent variables of task completion time and integrated curvature with fixed within-subject factors of trial type (planned vs. reactive) and endpoint cone number (1, 2, 3, 4) and the random factor of subject (Subject A vs. Subject B). A multifactor analysis of variance model was also fit for the dependent variable of path length with fixed within-subject factors of trial type (planned vs. reactive), endpoint cone number (1, 2, 3, 4), and body location (left foot, right foot, sacrum) and the random factor of subject (Subject A vs. Subject B). Normality was assessed by plotting a histogram of the observed data and residual of the model and calculating skewness. Completion time data were log transformed for left skewness, path length data were square-root transformed for right skewness and integrated curvature data were square-root transformed for right skewness. Constant variance of the model residuals was checked for each of the metrics using the Brown-Forsythe test. Following identification of significant main and interaction effects from the n-way ANOVA analyses, Tukey *post hoc* pairwise comparisons were completed.

Comparison of Vicon and IMU Estimates of Integrated Curvature - Hypothesis (3)

Since the Vicon and IMU trajectories are based off of different measurement methods for the same trials, they are dependent samples in this analysis. For each foot, integrated curvature is calculated based off of the Vicon positional trajectories ($IntCurv_{Vicon}$) and the IMU positional estimates ($IntCurv_{IMU}$). The paired difference D is calculated:

$$D = IntCurv_{Vicon} - IntCurv_{IMU} \tag{3.1}$$

The variable D was evaluated using a paired t-test to investigate if there is a signficant difference between Vicon- and IMU-based estimates of integrated curvature. A multifactor analysis of variance model was also fit for the dependent variable D with fixed within-subject factors of trial type (planned vs. reactive), endpoint cone number (1, 2, 3, 4), and body location (left foot, right foot) and the random factor of subject (Subject A vs. Subject B). Normality was assessed by plotting a histogram of the observed data and residual of the model and calculating skewness. The assumption of constant variance was checked using the Brown-Forsythe test. Following identification of significant main and interaction effects from the n-way ANOVA, Tukey *post hoc* pairwise comparisons were completed. The dependent variable D was also calculated for the smoothed Vicon and IMU trajectories. A similar analysis of variance model was fit and evaluated using the same process as the unsmoothed trajectories.

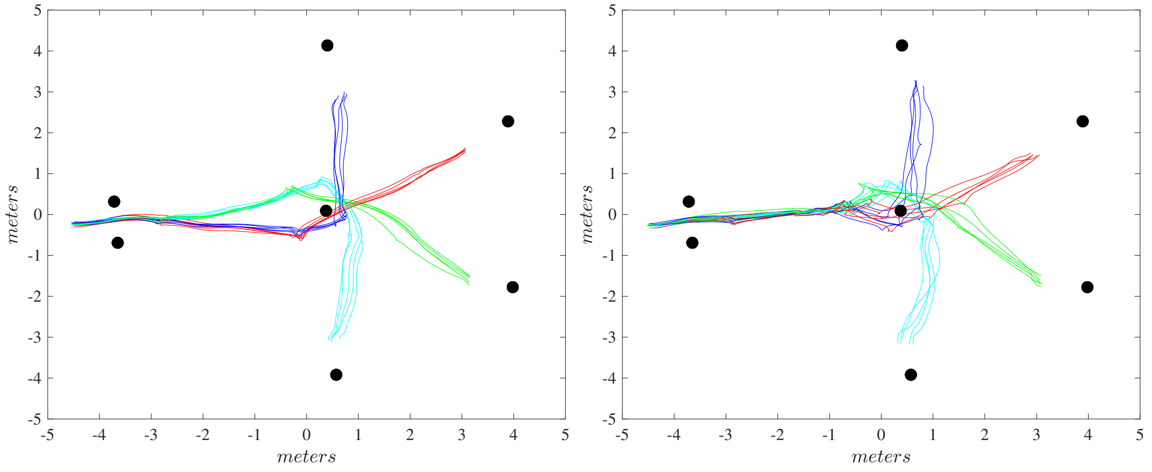
Following the paired difference analysis, the IMU-based integrated curvature data was then evaluated to test if similar conclusions could be reached as the Vicon-based comparisons. These evaluations were completed for both unsmoothed and smoothed IMU estimates. Based on the IMU-based trajectory estimates, separate multifactor analysis of variance models were fit for the dependent variables of unsmoothed integrated curvature and smoothed integrated curvature with fixed within-subject factors of trial type (planned vs. reactive), endpoint cone number (1, 2, 3, 4), and body location (left foot, right foot) and the random factor of subject (Subject A vs. Subject B). Normality was assessed by plotting a histogram of the observed data and residual of the model and calculating skewness. Unsmoothed integrated curvature data were square-root transformed for right skewness and smoothed integrated curvature data were log-transformed for right skewness. Constant variance of the model residuals was checked for each of the metrics using the Brown-Forsythe test. Following identification of significant main and interaction effects from the n-way ANOVA analyses, Tukey *post hoc* pairwise comparisons were completed.

3.3 Results and Discussion

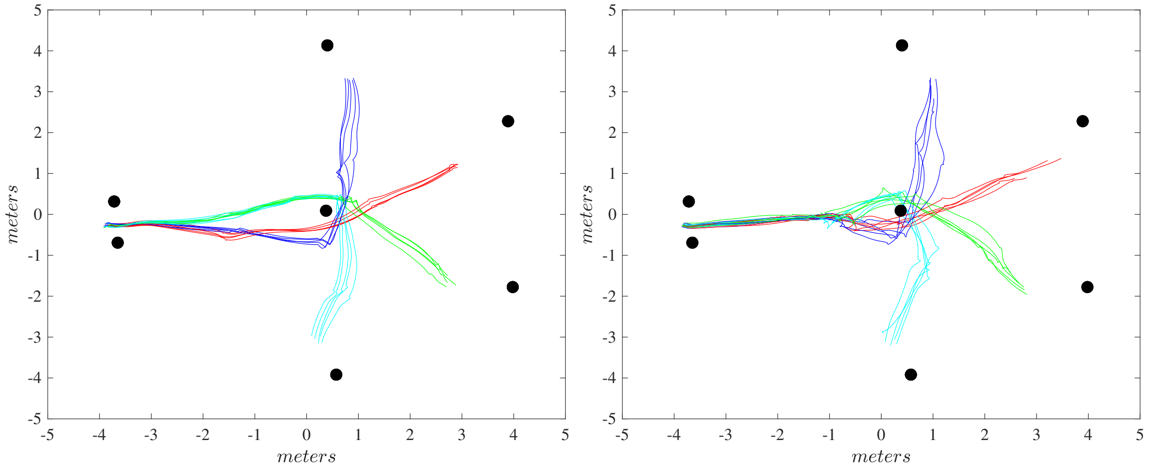
3.3.1 Evaluation of Hypotheses (1) and (2)

The positional trajectories as captured by the Vicon markers were recorded for both subjects for all planned and reactive agility trials. The path trajectories from both subjects are shown in Fig. 3-4 and Fig. 3-5.

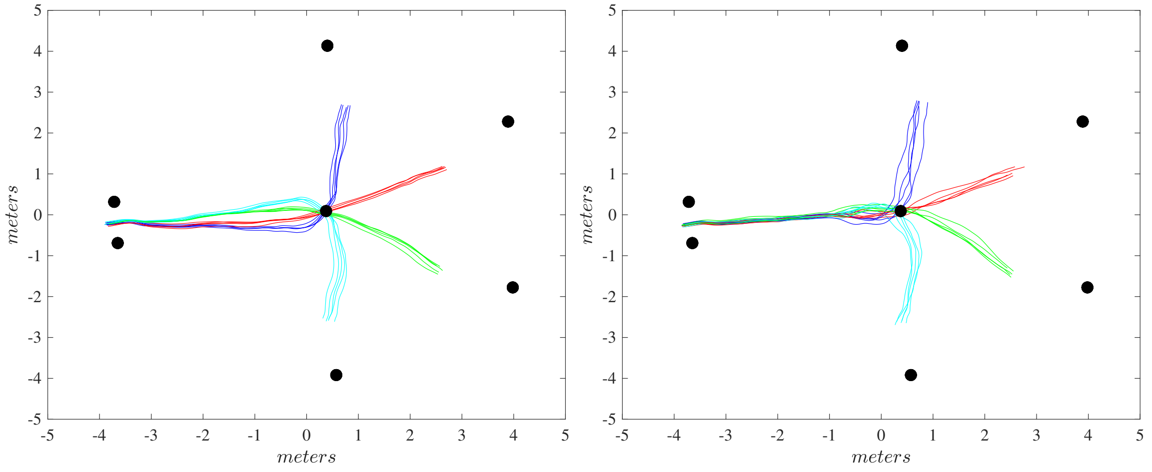
The planned agility trials shown (a),(c), and (e) of Fig. 3-4 and Fig. 3-5 suggest



(a) Planned Left Foot (b) Reactive Left Foot

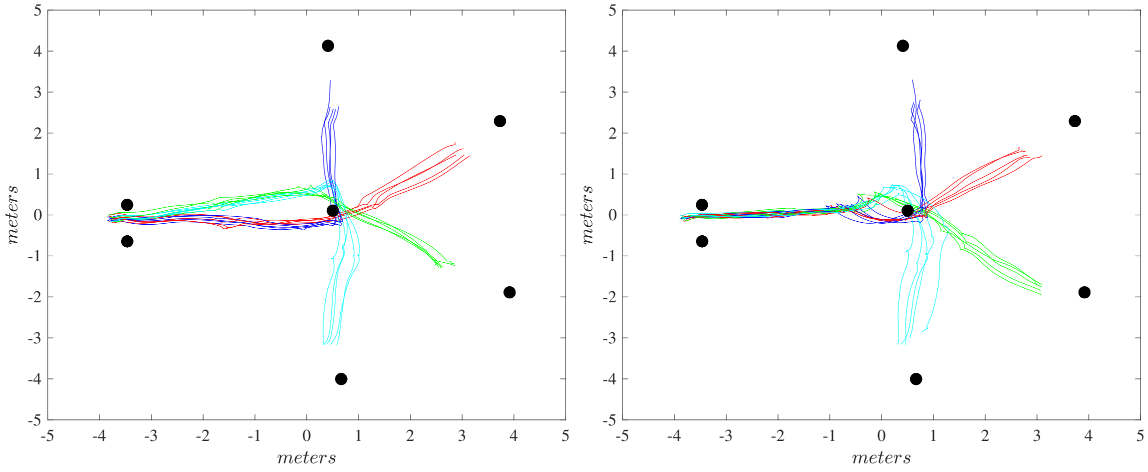


(c) Planned Right Foot (d) Reactive Right Foot

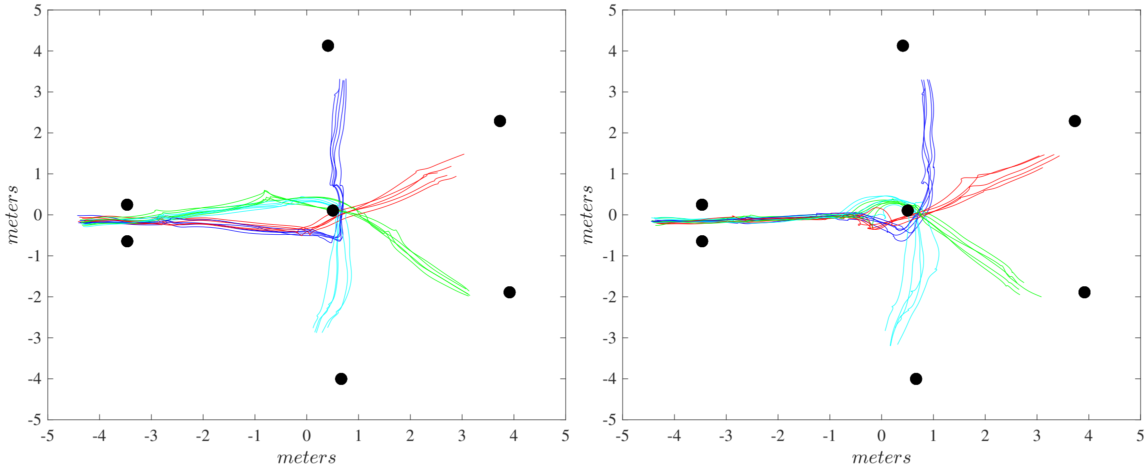


(e) Planned Sacrum (f) Reactive Sacrum

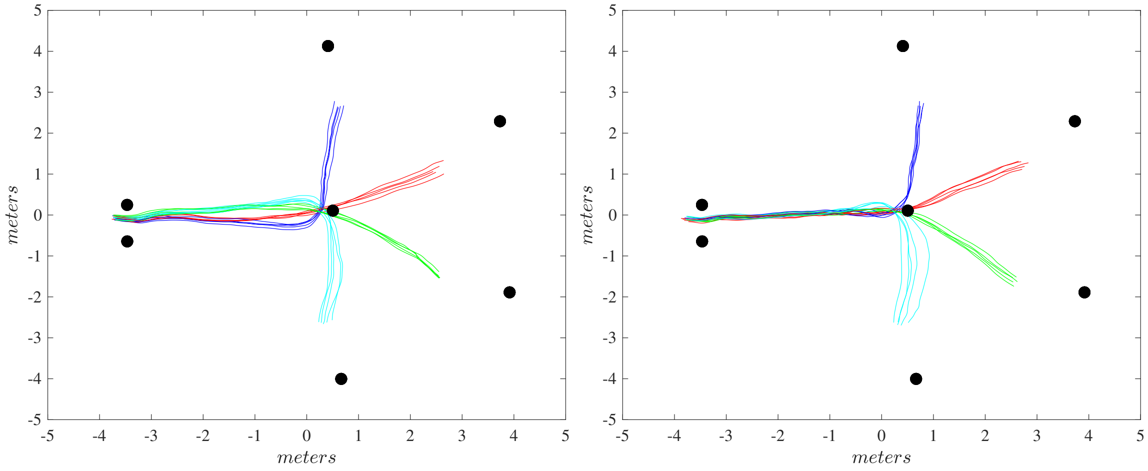
Figure 3-4: Complete Path Trajectory Set for Subject A. Black circles mark cone locations. Path trajectories of the same color denote multiple trials to the same cone. Planned trajectories are shown in (a),(c) and (e) while reactive trajectories are shown in (b),(d) and (f).



(a) Planned Left Foot (b) Reactive Left Foot



(c) Planned Right Foot (d) Reactive Right Foot



(e) Planned Sacrum (f) Reactive Sacrum

Figure 3-5: Complete Path Trajectory Set for Subject B. Black circles mark cone locations. Path trajectories of the same color denote multiple trials to the same cone. Planned trajectories are shown in (a),(c) and (e) while reactive trajectories are shown in (b),(d) and (f).

that subjects planned their routes from the beginning of their runs at the start cones. From the start cone to waypoint cone, these trajectories curve outwards in the direction opposite to their directed endpoint cone. These curved trajectories originate at the start cones. On the other hand, the reactive agility trials shown in (b), (d), and (f) of Fig. 3-4 and Fig. 3-5 exhibit straight trajectories up until the point where the verbal cue would be given (1.4 meters from the waypoint cone). For the reactive agility trials, the curved trajectories began near the point at which the task goal was made known to the subject. Comparing the planned and reactive trajectories suggests that subjects started planning their route at the point when they became aware of the endpoint, selecting a solution that increased curvature once the endpoint was known. During testing, subjects had been instructed to run around the waypoint cone. The path trajectories show that these instructions were executed for the foot trajectories, but subjects did not interpret the instructions to mean the whole body. For both planned and reactive trials, sacral path trajectories (Fig. 3-4e, 3-4f, 3-5e, 3-5f) often passed directly over or beyond the waypoint cone as subjects leaned over the cone during turning periods.

The ANOVA model (Appendix D) for completion time supports statistically significant mains of trial type ($F(1, 64) = 358.19, p < 0.05$) and endpoint cone ($F(3, 64) = 11.72, p < 0.05$). Tukey *post hoc* comparisons were completed for significant factors and boxplots of pairwise comparisons are shown in Fig. 3-6. For all endpoints, reactive agility trials had longer completion times (Fig. 3-6) than planned agility trials. The increased completion time for the reactive agility trials could be attributed to subjects' reaction time upon receiving the verbal cue. Upon receiving the verbal cue, subjects would need to plan their trajectory towards the now known endpoint cone and transition from anticipatory stutter-stepping to running around the waypoint cone to the endpoint cone. This planning and transition part of the reaction to the verbal cue could have contributed to longer completion times. Within the planned agility trials, completion times were higher for cones 1 and 4, which required 90° turns, than cones 2 and 3, which required 60° turns (Fig. 3-6). Similar comparisons were not found to be significantly different for reactive agility trials. Regardless of

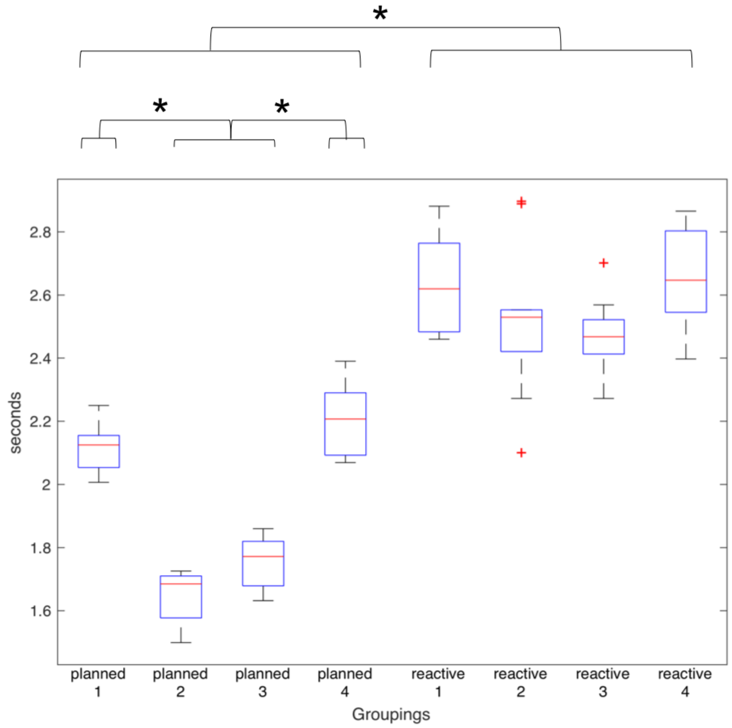


Figure 3-6: Completion time (sec) - Boxplot of Tukey *post hoc* pairwise comparisons for Vicon-based completion time (* indicates $p < 0.01$). Completion time comparisons between planned and reactive agility groupings for each cone.

endpoint cone, subjects had to run the same distance since each cone was 4 meters away from it's adjacent cone. Therefore, the results suggest that greater turn angles contributed to increased completion times within planned agility. This conclusion is consistent with prior work that showed for a similar course layout and task, inner cones had a greater cone acceleration than the outer cones [28].

For integrated curvature, the ANOVA model (Appendix D) supports a significant main effect for trial type ($F(1,64) = 190.67, p < 0.05$) and endpoint cone ($F(3,64) = 148.65, p < 0.001$). For all endpoints, reactive agility trials had higher integrated curvatures (Fig. 3-7) than planned agility trials. Within the planned agility trials, integrated curvatures were higher for cones 1 and 4 than cones 2 and 3 (Fig. 3-7). Within reactive agility, only cone 3 was less than cones 1 and 4 ($p < 0.05$). The endpoint cone differences are partly due to task definition. The outer cones (cones 1 and 4) inherently require a greater curvature to quickly cut around the larger turn

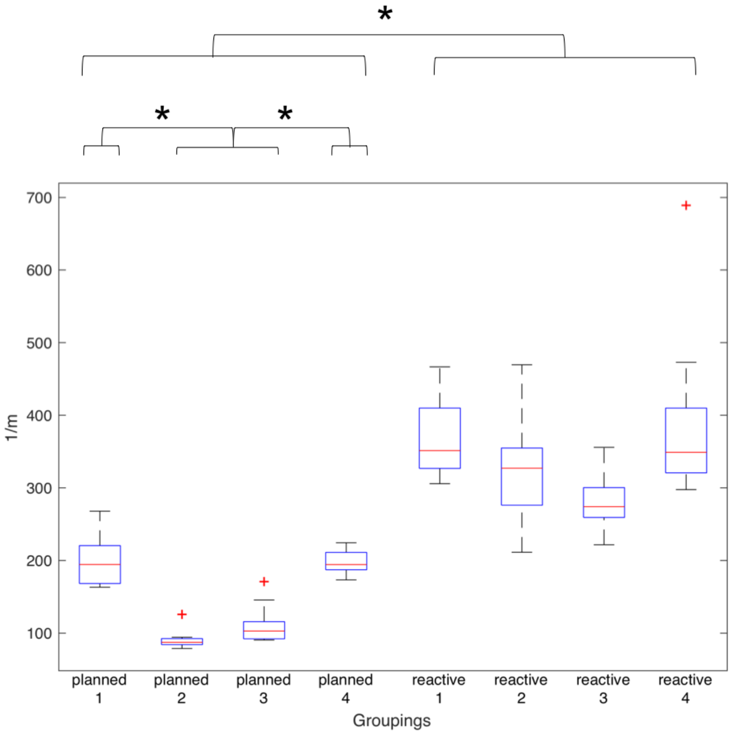


Figure 3-7: Integrated Curvature (1/m) - Boxplots of Tukey *post hoc* pairwise comparisons for Vicon-based integrated curvature of sacrum (* indicates $p < 0.01$). Integrated curvature comparisons between planned and reactive agility groupings for each cone.

angle, so it makes sense that those cones have larger integrated curvatures. However for reactive agility, this difference is only observed for one of the inner cones. This could be partly due to the lack of subjects since the data was collected as a pilot study. Another contributing factor could be that the higher overall curvatures for reactive agility trials reduces the inner vs. outer cone differences. Since subjects could not plan their entire trajectory at the start, it necessitates a sharper turn near where the verbal cue is heard, regardless of the eventual endpoint cone, as is observed in sub-figures (b), (d), and (f) of Fig. 3-4 and 3-5.

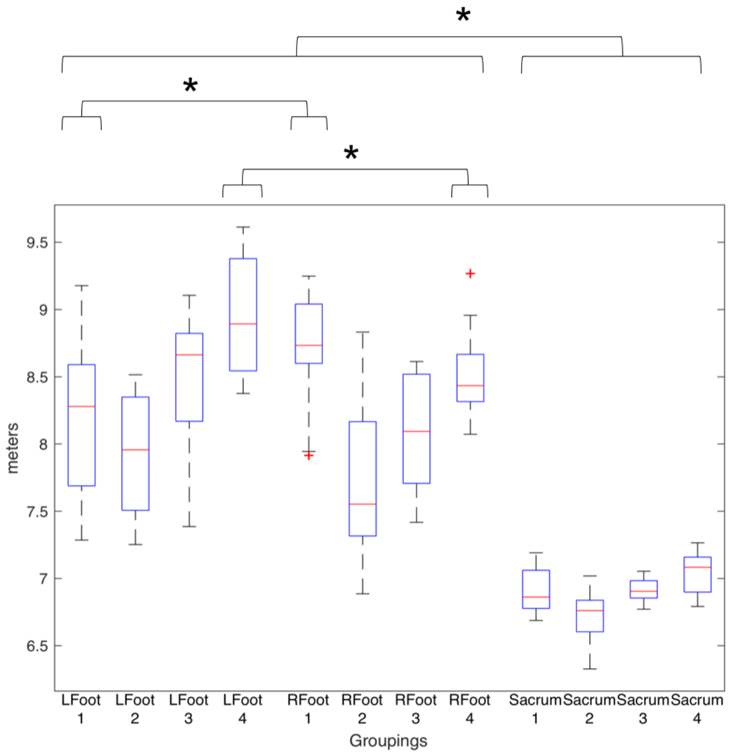
For path length, the ANOVA model (Appendix D) supports a significant main effect for endpoint cone ($F(3, 188) = 44.41, p < 0.01$); however there was also a significant interaction effect between endpoint cone and body location ($F(6, 188) = 7.02, p < 0.05$) and an interaction effect between all factors ($F(6, 188) = 2.78, p <$

0.05). The left and right foot path lengths were larger than sacral path lengths for all endpoint cones (Fig. 3-8a). In comparing the foot path lengths, for cone 1 the right foot had larger path lengths than the left foot. For cone 4, the left foot had larger path lengths than the right foot. Thus for cones 1 and 4, the outer turning foot had larger path lengths than the inner foot. This effect was not observed for cones 2 and 3. Analysis of path length also showed that while Subject A did not demonstrate significant differences between planned and reactive agility, for Subject B planned agility trials were significantly smaller in path length than reactive agility trials (Fig. 3-8b).

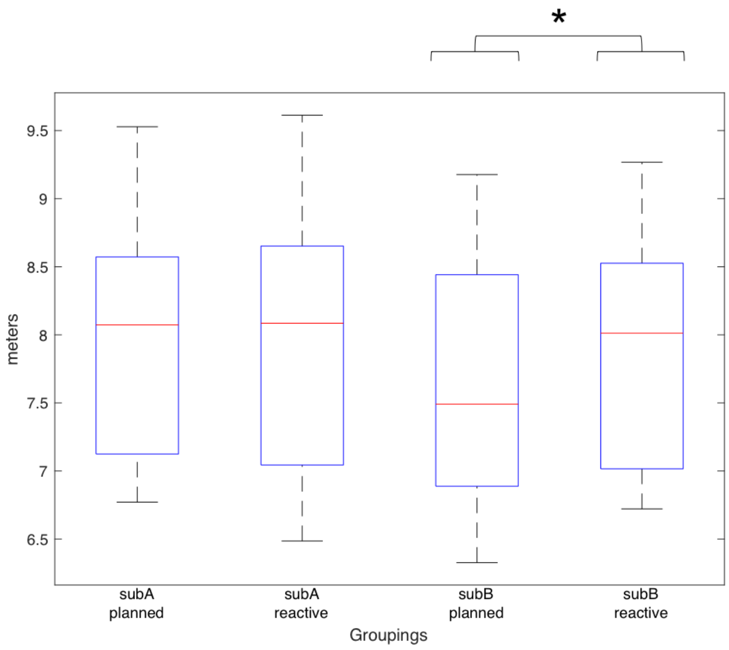
Trial type was not found to have a significant effect on path length, regardless of the body location measured or endpoint cone. Fig. 3-4 shows that the reactive agility trajectories are characterized by a straightaway portion up until the cue point is given, followed by a sharp turn around the waypoint cone towards the endpoint cone. Whereas the planned agility trajectories demonstrate a continuous curved trajectory. For the case of this pilot study, path length may not have been a strong discriminator between planned and reactive agility due to differences in when curved portions of the trajectory originated and how sharp those curved portions were. However, trial type was found to have a significant effect on integrated curvature, which suggests that this metric may be better suited towards characterizing curved portions of the positional trajectories.

3.3.2 Comparison of Vicon and IMU Estimates of Integrated Curvature - Hypothesis (3)

The IMU-based positional trajectories were evaluated for both subjects for all planned and reactive agility trials. A representative sample for a planned agility trial is shown in 3-9. Qualitatively, the overall shape of the IMU and Vicon-based trajectories are similar. However the IMU trajectories are somewhat truncated, originating around the turn about the waypoint cone. Since the algorithm used by Ojeda and Borenstein [19] relies upon a zero-velocity foot update, it is hypothesized that the high velocity

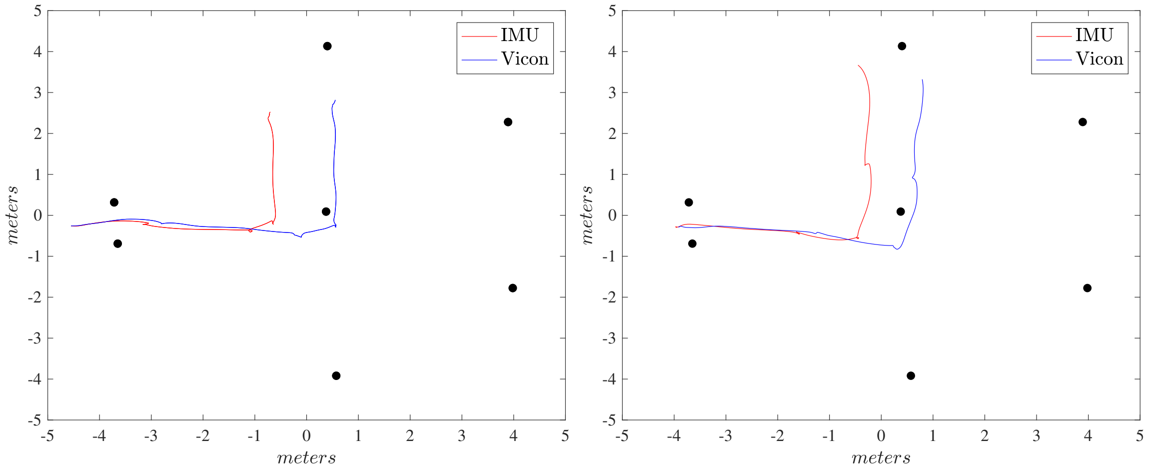


(a)



(b) Path Length (meters)

Figure 3-8: Boxplots of Tukey *post hoc* pairwise comparisons for Vicon-based path length (* indicates $p < 0.01$). (a) Path length comparisons between the left heel, right heel and sacrum for each cone. (b) Path length comparisons between each subject for each trial type



(a) Left Foot IMU vs Vicon Trajectory (b) Right Foot IMU vs Vicon Trajectory

Figure 3-9: IMU- vs Vicon-based positional trajectories for a planned agility trial to endpoint cone 1 by Subject A. Foot trajectories based on Vicon markers are in blue while IMU-based estimated trajectories are in red. (a) Left foot trajectory. (b) Right foot trajectory.

footfalls and pivoting action of the foot about the waypoint cone (which would not result to a zero velocity in magnitude) may result in accurate trajectory estimates, which are compounded by the aforementioned drift error. Therefore, metrics such as path length are not suitable for analysis in comparing the Vicon and IMU-based trajectory estimates. However, it is also hypothesized that the trajectory estimates in between footfalls are similar such that the overall curvature of the trajectories are not significantly different. Thus further analysis to compare the Vicon and IMU-based trajectory estimates uses the integrated curvature metric.

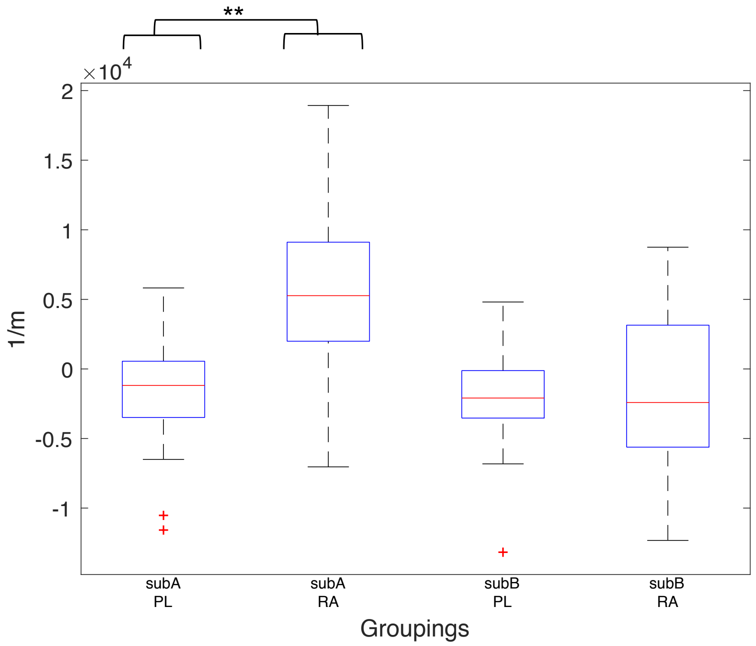
$D_{unsmooth}$ Analysis

For the paired difference variable $D_{unsmooth}$ calculated with the unsmooted Vicon and IMU-based trajectories, the t-test failed to reject the null hypothesis that $D_{unsmooth}$ was not different from zero. While the entire distribution of $D_{unsmooth}$ was evaluated with the t-test, the ANOVA analysis investigates whether any factors within the distribution were significantly different from other factors. The ANOVA model (Appendix D) for the variable $D_{unsmooth}$ supports a statistically significant main effect for body location ($F(1, 118) = 256.72, p < 0.05$) and interaction effects for trial type and body location ($F(1, 118) = 8815.79, p < 0.01$); trial type and subject ($F(1, 118) = 30.13, p < 0.05$); and trial type, endpoint cone, and body location ($F(3, 118) = 12.83, p < 0.05$). Tukey *post hoc* comparisons were completed for the significant factors. Between feet, $D_{unsmooth}$ on the right foot was greater than the left foot. Within Subject A's trials, reactive agility trials were found to have greater $D_{unsmooth}$ than planned agility trials (Fig. 3-10a). Furthermore for cones 1, 2, and 4, $D_{unsmooth}$ on the right foot during reactive agility were greater than that on the left foot and greater than planned agility trials on the left foot (Fig. 3-10b).

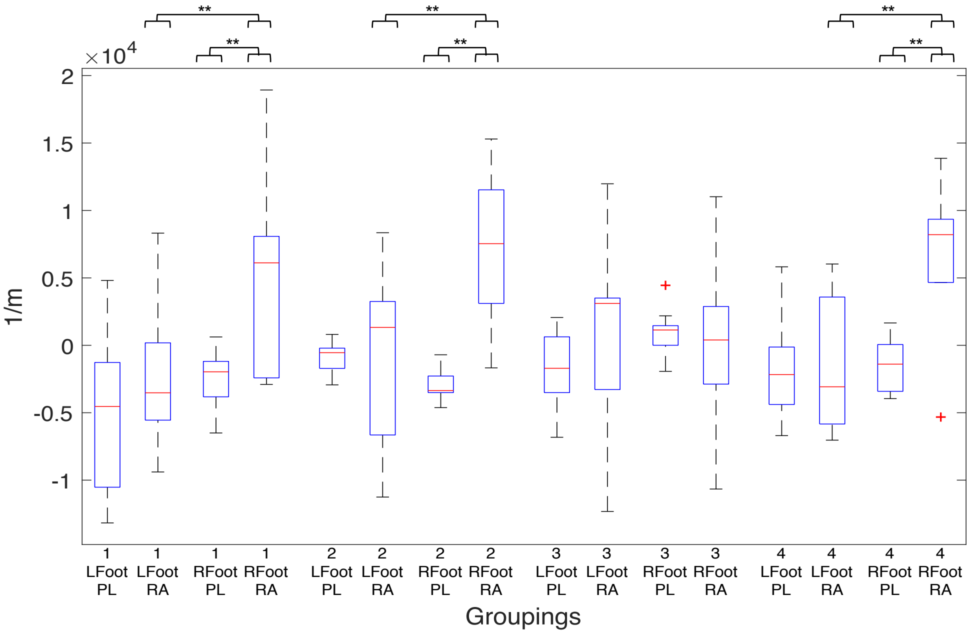
These significantly different groups had a mean value of $D_{unsmooth} > 0$ which means that the Vicon-based integrated curvatures for these trials was greater than the IMU-based integrated curvatures. An example of one of these trials is shown in Fig. 3-11. As shown in Fig. 3-11a, large spikes in the Vicon-based curvature can be observed in between 1.5 to 2 seconds, which corresponds to the portion of the trajectory right before the waypoint cone (around (-1.5-1m, 0m) in Fig. 3-11b and 3-11c). $IntCurv_{Vicon}$ were calculated based on the heel marker of the foot while $IntCurv_{IMU}$ were calculated based on IMUs mounted on the top of the foot. A contributing factor to the larger $IntCurv_{Vicon}$ could be that while anticipatory stutter-stepping before receiving a verbal cue, subjects' heels were bouncing and pivoting while the balls of their feet remained in place. These heel bounces and pivots could present as a bump in curvature in the X-Y plane, resulting in a larger overall integrated curvature. In terms of the right foot vs. left foot, these differences may be influenced by foot dominance. Both subjects self-reported being right foot dominant. It's possible that their right heels stutter-stepped more during reactive agility trials in anticipation of needing to turn direction and driving the directional change with their dominant foot. However such a strategy difference is difficult to significantly infer from a pilot study with two subjects.

D_{smooth} Analysis

Another possible reason is that throughout the trajectories at the footfall points, a sharp high curvature kink is prominent, such as near (-1m, 0m) in 3-9a and near

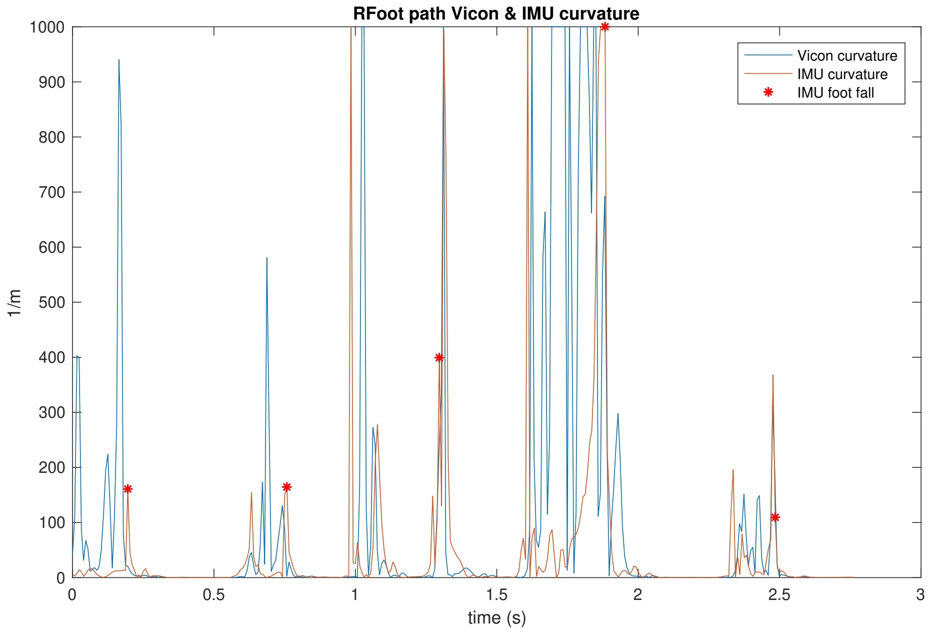


(a)

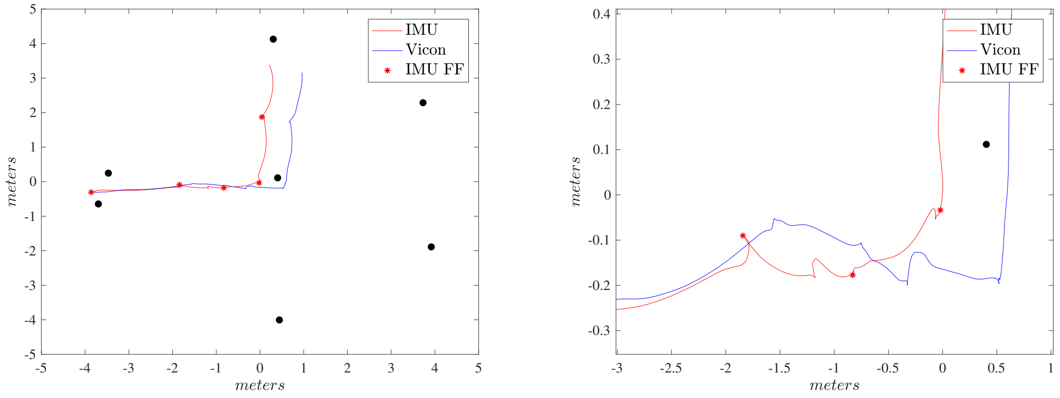


(b) Integrated Curvature ($\frac{1}{m}$)

Figure 3-10: Boxplots of Tukey *post hoc* pairwise comparisons for $D_{unsmooth}$ integrated curvature (** indicates $p < 0.001$). (a) $D_{unsmooth}$ comparisons between subject for each trial type. (b) $D_{unsmooth}$ comparisons between trial type for each foot and cone.



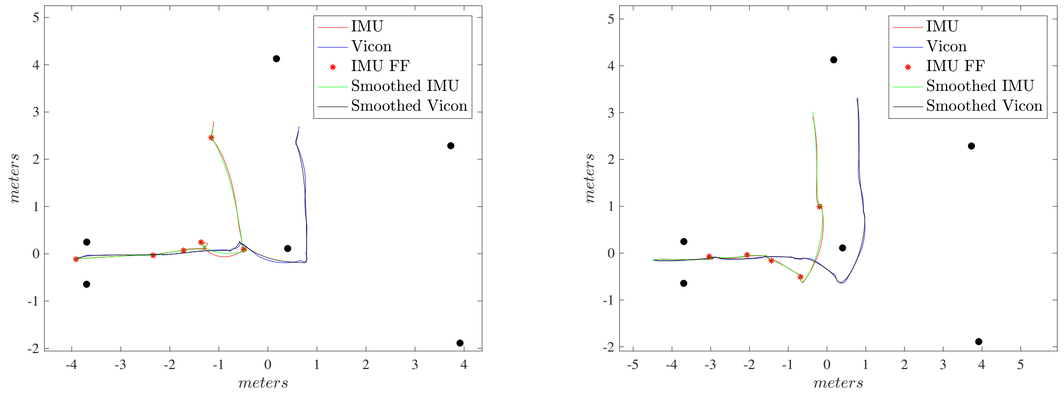
(a) Instantaneous path curvature over time for right foot



(b) Right foot path trajectory

(c) Zoomed in trajectory

Figure 3-11: Edge case of extreme positive difference ($D = 18932\frac{1}{m}$) between Vicon and IMU-based trajectories.



(a) Left Foot

(b) Right Foot

Figure 3-12: Smoothed Vicon and IMU-based trajectories are plotted against the original trajectories. The original Vicon trajectory is in blue and the original IMU trajectory is in red. Red asterisks mark where the algorithm from [19] identified footfalls. Smoothed Vicon trajectories are overlaid in black and the smoothed IMU trajectories are overlaid in green. This represents a sample reactive agility trial of Subject B running to cone 1.

(0m,1.5m) in 3-9b. Comparisons between Vicon and IMU-based trajectories at these points may be affected by saturation of the accelerometers of the IMUs during high velocity footstrikes and stutter stepping during reactive agility trials. While the curvatures at these footfalls may be different between methods, it's possible that the portion of the trajectories between the footfalls have similar curvatures. To investigate this further, comparisons between smoothed Vicon and IMU-based trajectories were analyzed. An example of these smoothed trajectories is shown 3-12.

From these smoothed trajectories, integrated curvatures and the metric D_{smooth} were calculated. Using a paired t-test, D_{smooth} was found to be less than zero ($p < 0.0005$), indicating that the integrated curvatures of the IMU-based trajectories were greater than the Vicon trajectories since $D = IntCurv_{Vicon} - IntCurv_{IMU}$. Further analysis with ANOVA was utilized to investigate which factors had an effect on this difference. The ANOVA model (Appendix D) fit for the dependent variable D_{smooth} supports a significant interaction effect between trial type, body location, and subject ($F(1, 118) = 24.85, p < 0.05$). Tukey *post hoc* tests were completed for the significant factors. For Subject A, D_{smooth} on the right foot during reactive agility were greater

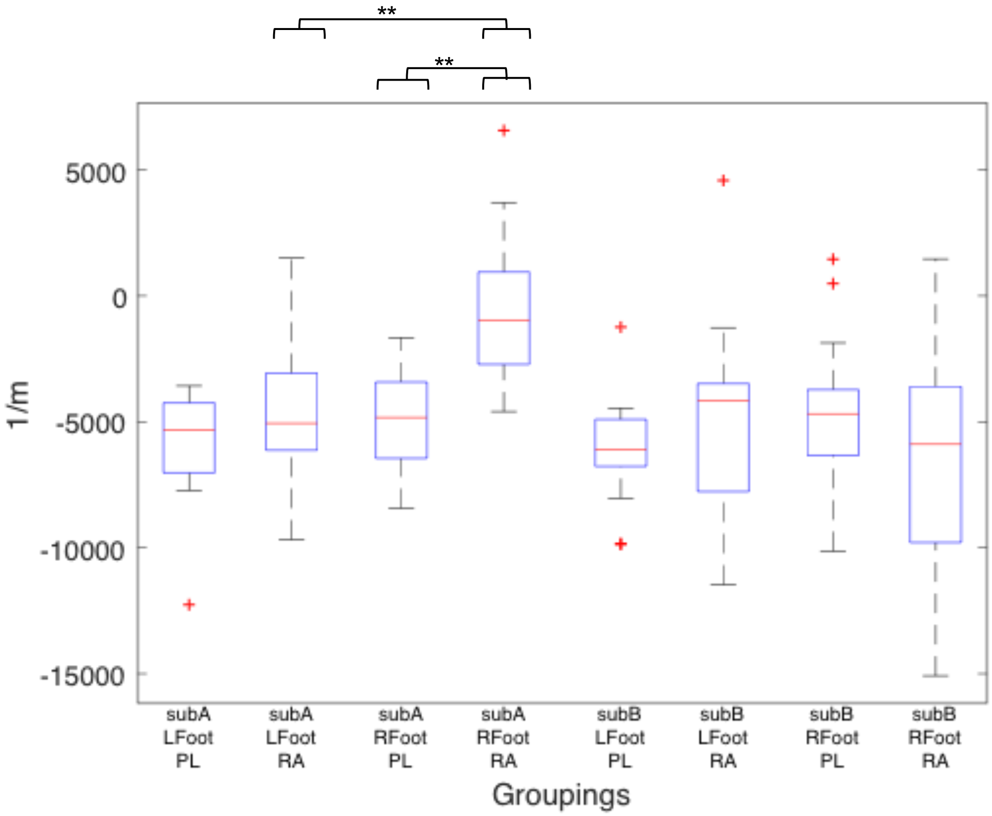


Figure 3-13: Boxplot of Tukey *post hoc* pairwise comparisons for D_{smooth} integrated curvature (** indicates $p < 0.001$). Comparisons for groupings of subject, body location and trail type.

than that on the left foot and greater than planned agility trials on the left foot (Fig. 3-13). Similar to the unsmoothed analysis, the reactive agility trajectories on the right foot of Subject A seem to have larger differences than the rest of the distribution of D_{smooth}.

A histogram of the distribution of D_{smooth} is shown in Fig. 3-14. Outlier cases were also identified by calculating cases where D_{smooth} was more than three scaled median absolute deviations away from the median (*isoutlier* function in Matlab). Of the total 160 trials (1 for each foot), 7 cases were outliers. Four were for Subject A, three were for subject B, and all but two occured for the right foot. Six edge cases were for reactive agility trials and five involved a 90° turn. For one of the reactive agility trials to cone 4 by Subject B, $D_{smooth} = -15082\frac{1}{m}$ for the right foot. The overall trajectory of this case is shown in Fig. 3-15b and the time varying instantaneous curvature throughout the trajectory is shown in Fig. 3-15a. A large spike in curvature is seen prior to the first footfall identified by the IMU algorithm before the 0.5 sec mark and large spikes accompany each of the identified footfalls. Fig. 3-15c shows a zoomed in view around the first, second, third, and fourth identified footfalls. While the smoothed Vicon trajectory in black smooths out the kinks at the identified footfalls, the smoothed IMU trajectory around the footfalls still have sharp peaks and even loops. These footfalls occurred after the start cone and just before where the verbal cue would have been given at (-1.33m, 0m). The high curvatures for the IMU based trajectory may be affected by the parameters of the smoothing function not being optimized for this case and quick stutter steps taken by the subject before the cue was given. The fact that the mean of D_{smooth} was less than zero while the mean of $D_{unsmooth}$ was not significantly different from zero suggests that the smoothing process affected the Vicon trajectories more than the IMU trajectories. Some features of the IMU trajectories, such as the small loop seen around (-1.25m, -0.1m) in Fig. 3-15c would be difficult for the *csaps* function to smooth out. Whereas the portion of the blue Vicon trajectory near that step (-0.8m, -0.1m) exhibits a small peak that is smoothed out in black. Such loop features near the identified footfalls for the IMU-based trajectories are present for multiple trials, albeit they are smaller than the ones present in the outlier cases. Thus smoothing out the trajectories has a larger effect on the Vicon-based trajectories than the IMU-based trajectories.

Other options could be investigated to optimize the parameters of the *csaps* function or use a different method like a low-pass filter. But first a standard would need to be identified to ascertain when the smooth IMU-based trajectories have metrics similar enough to the Vicon-based trajectories. Such a standard could involve smoothing enough so that D_{smooth} is not significantly different from zero or it could be a point where even though D_{smooth} is different, similar integrated curvature comparisons emerge from solely IMU based trajectories and solely Vicon based trajectories. Such optimization is difficult to determine at a general scale for the population of interest since this pilot data set is drawn from just two male subjects with very similar athletic backgrounds. Three of the outlier cases (with slightly positive D_{smooth}) also come from the right foot of Subject A on reactive agility trials, a similar category to the factors that were significantly different in the $D_{unsmooth}$ analysis. While smoothing the IMU-based trajectories affected the entire distribution of D, it did not necessarily mitigate all the differences that were tied to specific factors. With the pilot data set, it is difficult to determine if these differences are due solely to the differences between the heel-based Vicon trajectory and the IMU-based trajectory, subject strategy based on dominant foot, or just a small data set. Optimizing the smoothing technique also would not be possible in situations where a Vicon-based doesn't exist for comparison. Consequently, instead trying to optimize the IMU-based trajectory to be as similar as possible as the Vicon-based trajectory, it may be more feasible to investigate if similar decision-making conclusions can be made with both measurement platforms using the integrated curvature metric.

While D_{smooth} was found to be less than zero, the ANOVA model fit for D_{smooth} supports that there are less main and interaction effects than when the trajectories are unsmoothed. Even if D_{smooth} is negative, if the differences based on trial type, cone, and body location can be minimized, it's possible that solely IMU-based metrics could be utilized in a decision-making capacity similar to the Vicon metrics. While the integrated curvature values may be different, the comparative conclusions based on the metric could be parallel from Vicon- and IMU-based trajectories. Thus the following section will investigate the degree to which solely IMU-based integrated curvature estimates can replicate the Vicon-based estimate comparisons from Section 3.3.1.

$IntCurv_{IMU}$ Analysis

The results from Section 3.3.1 concluded that within planned agility trials, integrated curvature was larger for the outer cones than the inner cones and that all reactive agility trials had greater integrated curvature than all planned agility trials. An ANOVA model was fit for the dependent variable $IntCurv_{IMU}$ for unsmoothed IMU-based trajectory estimates to investigate if similar conclusions could be made. For

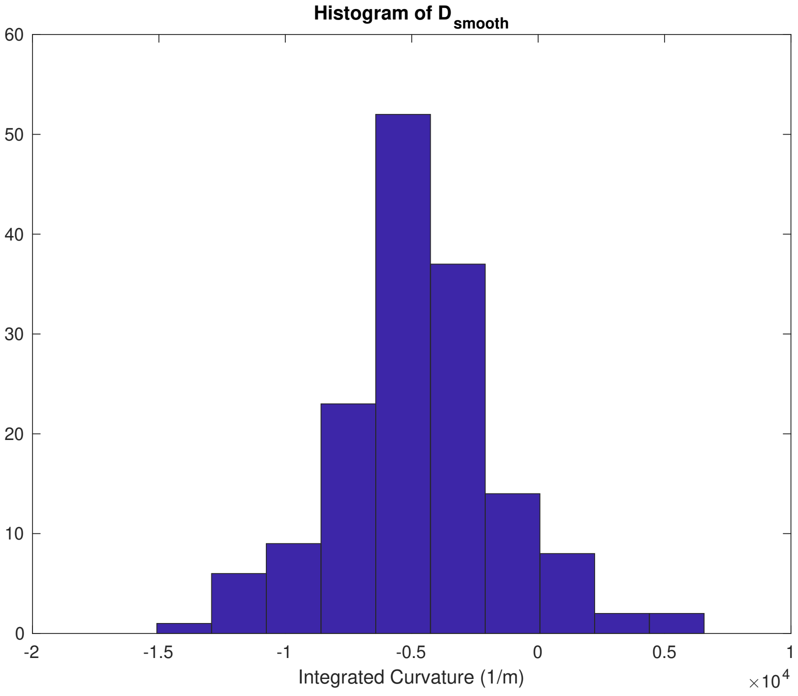
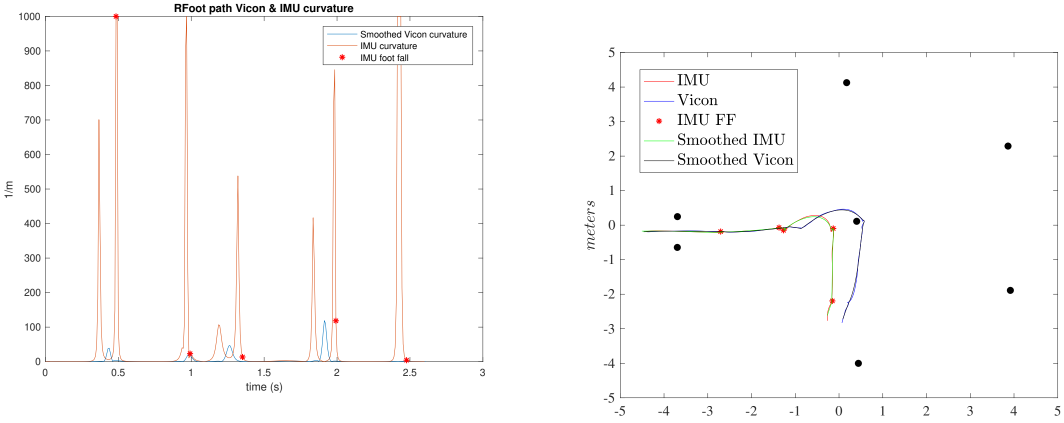
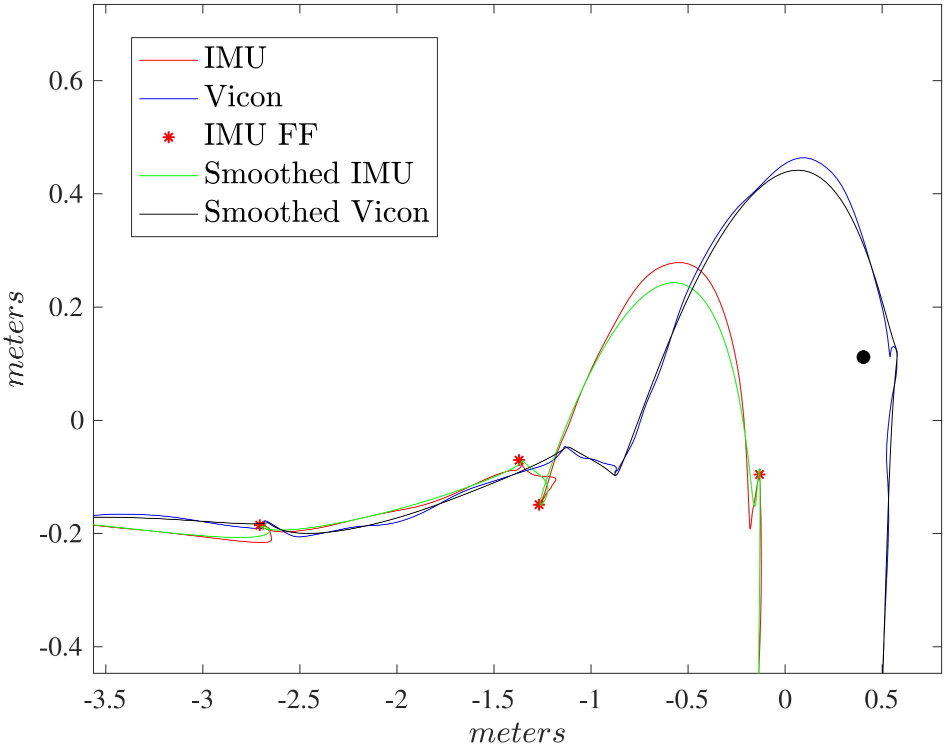


Figure 3-14: Histogram of distribution of D_{smooth}. The shape of the distribution follows a normal distribution and normality was verified before the ANOVA model was fit. The mean of D_{smooth} appears to be negative (suggesting that $IntCurv_{IMU}$ is greater than $IntCurv_{IMU}$); however, there are still negative and positive outliers.



(a) Instantaneous path curvature over time for right foot

(b) Overall path trajectory for right foot



(c) Zoomed in trajectory

Figure 3-15: Edge case of extreme negative difference ($D_{smooth} = -15082\frac{1}{m}$) between Vicon and IMU-based trajectories.

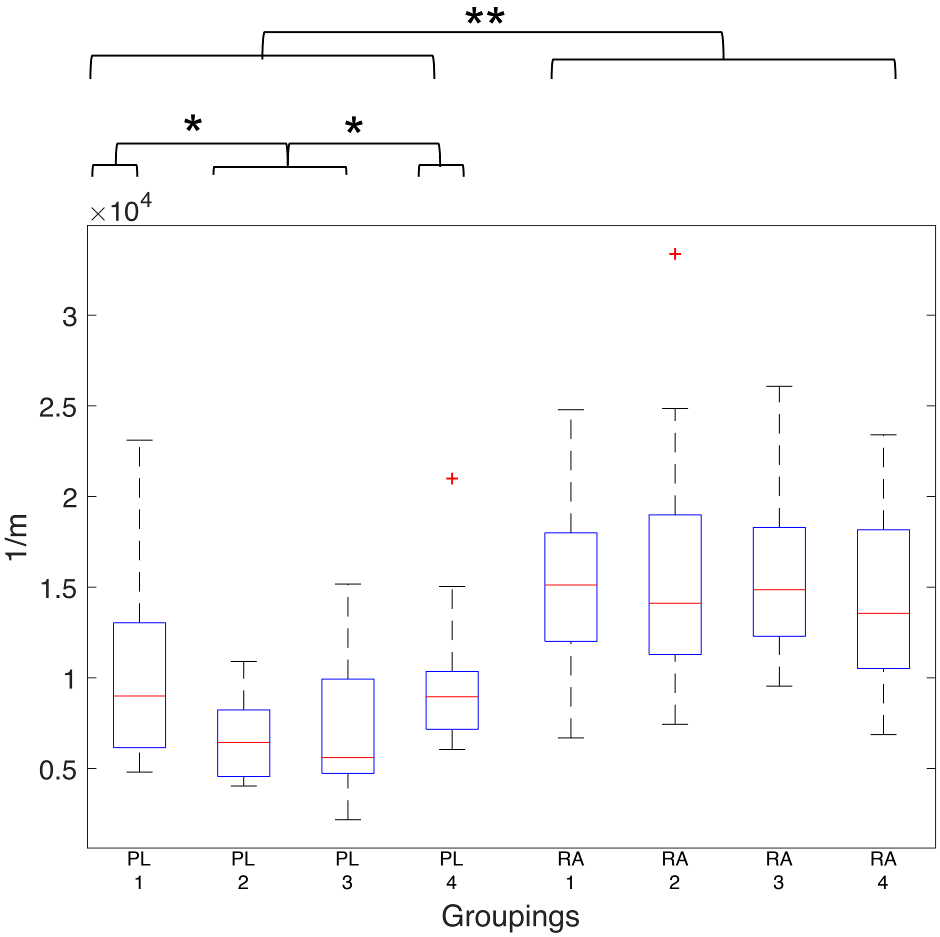


Figure 3-16: Integrated Curvature (1/m) - Boxplots of Tukey *post hoc* pairwise comparisons for Unsmoothed $IntCurv_{IMU}$ (* indicates $p < 0.01$, ** indicates $p < 0.0001$). Integrated curvature comparisons between planned and reactive agility groupings for each cone.

unsmoothed $IntCurv_{IMU}$, the ANOVA model (Appendix D) supports significant interaction effects between trial type and cone ($F(3, 122) = 9.53, p < 0.05$) and between trial type, cone, and body location ($F(3, 122) = 30.67, p < 0.01$). For all endpoints, reactive agility trials had higher integrated curvatures (Fig. 3-16) than planned agility trials. Within the planned agility trials, integrated curvatures were higher for cones 1 and 4 than cones 2 and 3 (Fig. 3-16). These conclusions on integrated curvature are similar to those made using the Vicon-based metric.

A similar analysis was also completed for the smoothed IMU-based trajectories.

For smoothed $IntCurv_{IMU}$, the ANOVA model (Appendix D) did not support any statistically significant main or interaction effects. However the interaction effect between trial type and cone ($F(3, 126) = 9.15, p = 0.0509$) is trending towards significance. Tukey *post hoc* comparisons on this effect showed that for only cone 2 ($p < 0.005$) and cone 3 ($p < 0.05$) did planned agility trials have less integrated curvature than reactive agility trials. Within planned agility trials, the outer cones had greater integrated curvature than the inner cones ($p < 0.05$). The effect size for the smoothed $IntCurv_{IMU}$ was not as large as the unsmoothed $IntCurv_{IMU}$ data. This may support that the metrics based on the unsmoothed trajectories are more appropriate for decision-making conclusions since they align more with the Vicon-based results.

3.4 Limitations

The results shown are limited to the testing of two subjects with similar athletic training. Most of the analysis is limited to within-subject factors. Fig. 3-8b suggests that trial type may have an effect on path length, but the small subject set limits generalization. In representing the foot for Vicon-based trajectories, the heel marker was chosen because it had the least amount of marker dropout during data processing. Initially the markers placed on the IMU marker plate were of interest, but these markers often dropped out of camera view during the swing phase of running and were not eligible for gap-filling techniques. Using the heel marker to represent the foot may have affected results during trial portions when the subject is pivoting on their foot, particularly when turning around the waypoint cone. During such portions, the subject may be pivoting in place on the balls of their feet while their heels are in motion. While the entire foot was not translating, a curved trajectory would be recorded during these trial portions as the heel rotated around. This may have resulted in increased integrated curvatures and path lengths for the pivoting foot. Foot pivoting may have also resulted in the loop features exhibited in the IMU-based trajectories, especially if the foot was pivoting and sliding. These loop features would also contribute to increased integrated curvatures and path lengths for the IMU-based trajectories.

Setting a 0.85 meter boundary from the endpoint cone excluded the portions of the run when the subject was leaning down to touch the endpoint cone, turning and running back to the Start cones. Setting this boundary reduced high curvature portions of the trajectories during the turning periods around the endpoint cones that initially confounded the integrated curvature data and set a standard end point for all trials. However, this also meant that these 180° turns were excluded from the agility analysis.

The IMUs had been placed on top of the midfoot and thus the IMU-based trajectories represented a slightly different part of the foot when compared to the Vicon-based trajectories (heel marker). Such differences may have contributed to some of the outlier D values, especially during pivoting sections about the waypoint cone and when a subject stutter steps in anticipation of receiving a verbal cue to the endpoint cone. For two of the trials, the subjects did not stand still for enough time before preparing to run. The standing still period is needed by the foot trajectory algorithm [19] to establish a threshold for detecting the zero velocity point during a foot fall. Inadequate still periods may have also contributed to inaccuracies in the IMU-based trajectories.

3.5 Conclusions

In this study, it was hypothesized that based on Vicon marker analysis (1) trial type (planned vs. reactive) contributes significantly to task completion time, integrated curvature and path length; and, (2) path lengths differ between the feet and sacrum of a subject. It was also hypothesized that the curvature profile for IMU-based estimates are not significantly different from the curvature profile of the Vicon-based estimates (3).

Based on this pilot study, Vicon-marker analysis of subjects showed that trial type (planned vs. reactive agility) contributes significantly to task completion time and integrated curvature. Trial type did not have a significant effect on path length of the runs. Path lengths of the sacrum were found to be significantly less than that of the feet for all trial types. Further analysis of cones that required 90° turns vs 60° turns suggests that, for at least planned agility, knowledge of the location for a task goal may affect subject strategy as the outer foot of the sharper turns demonstrated larger path lengths. Path layout and the availability of *a priori* knowledge of task goals may have a significant effect on how subjects strategize task completion for an agility-based run. Analysis of the paired difference of integrated curvature between Vicon-based and IMU-based trajectories showed that while the overall paired difference was not significantly different than zero, for certain factor scenarios, IMU-based trajectories had significantly greater integrated curvatures than Vicon-based trajectories. To investigate if these factor-based differences could be mitigated, the trajectories were smoothed out and the paired differences between integrated curvatures were analyzed. IMU-based integrated curvature measures were found to be significantly greater than Vicon-based measures. Analysis of some edge cases where these differences were extreme demonstrated that while the edge cases occurred for both subjects and both feet, almost all involved reactive agility trials and almost all occurred for trials involving 90°turns. Although the actual integrated curvature values were different for some some factors, analysis of just the unsmoothed IMU-based integrated curvature metric resulted in comparative conclusions similar to those made of the Vicon-based integrated curvature. When the IMU-based trajectories were smoothed, the analysis on the integrated curvature metric did not support significant comparative differences, but effects were trending towards significance.

The results support hypothesis (1) for the completion time and integrated curvature metrics and the results support hypothesis (2). Hypothesis (1) for path length was not supported as trial type did not have a significant effect on path length. For the unsmoothed trajectories, the results support hypothesis (3).

This chapter investigated how different metrics could be utilized on different measurement platforms (Vicon motion capture and wearable IMUs) to characterize the path trajectories of human subjects completing a running agility task. The analysis demonstrated that the metric of integrated curvature could be utilized on both measurement platforms to make similar comparative conclusions on how trajectories differ. Particularly, trajectories differed dependent on whether the task goal was known *a priori* (planned vs. reactive agility) and the nature of the task definition (turns towards inner or outer cones). However differences were still present in some of the reactive agility trials, partly due to features caused by subjects stutter stepping. If the IMUs were used to quantify human movement and performance in reduced gravity environments, it's possible that that some of the reactive agility dependent differences could be mitigated. As modelled in Chapter 2, in reduced gravity conditions optimal trajectories would involve lower velocities and higher curvatures about turning regions, which could reduce the amount of stutter stepping. While there may be a bias in the magnitude of the IMU-based metrics, the trends across conditions are still detectable and consistent. Utilizing the integrated curvature with IMUs could offer an opportunity to better characterize experimental trajectories in varied gravity conditions in naturalistic operational environments.

Chapter 4

Accessibility of the Microgravity Research Ecosystem

Measurement of the agility-based human performance metrics relies upon access to systems and environments that afford measurement techniques. For measuring human performance terrestrially, motion capture systems are the gold standard for measuring kinematics, but are costly and limited to laboratory settings. Wearable technology like IMUs offer the opportunity to move beyond laboratory settings to naturalistic field conditions on the ground, but work is still ongoing to develop metrics for different aspects of human performance for the general population.

The spaces in which we measure human performance are not limited to just the ground, but include outer space as well. Through the history of human spaceflight, understanding how humans pilot spacecraft, operate technical systems, and live in microgravity environments has been a prime focus for civil space agencies engaged in human spaceflight. But in recent years this ecosystem has become more complicated and is evolving to include marketplaces for microgravity research and development as well. The following chapters investigate accessibility of the microgravity research ecosystem, with a particular focus on access for non-traditional spaceflight user groups. Beyond the technical operations, understanding how humans interact with these research platforms from a policy perspective is important for future accessibility to “spaces” in outer space.

4.1 Motivations

For decades, the International Space Station (ISS) has operated as a bastion of international cooperation and a unique testbed for microgravity research. Beyond enabling insights into human physiology in space, the ISS has served as a microgravity platform for numerous science experiments, technology demonstration projects, and outreach programs [153]. But just how "international" is the ISS? How accessible is it to different types of user groups around the world? The ISS is one of the largest and most expensive construction projects in human history. The development of the ISS took decades and is characterized by evolving priorities and socio-technical issues. Today it is an immensely complex conglomeration of technical systems, public and commercial modules, and public-private partnerships. And yet it works, maintaining operations coordinated across the globe for the past twenty years. Because of the ISS and the efforts to develop it, humans have lived in space continuously since the year 2000 [153].

In recent years, a combination of decreasing flight costs and the emergence of new models that invite participation of non-traditional actors have contributed to reducing the barriers of access to the ISS platform. As these non-traditional groups – such as startups, non-NASA and early career academics, emerging space nations, and education outreach groups – seek to participate in microgravity research, we begin to push at the edges of asking just how "international" the ISS actually is. How accessible is it to different types of user groups around world? Additionally, the ISS in its current form cannot be sustained forever and current hardware will eventually reach the end of its lifetime. As NASA looks towards commercialization of the low Earth orbit (LEO) space, concrete plans for shifting the public private relationship of the ISS and development of a commercial economy in LEO are unclear. With possible increases in demand for microgravity research – from governments and private industry – understanding the socio-technical and policy issues that affect the marketplace for future microgravity platforms is essential to maintaining an accessible and sustainable space economy.

4.2 Literature Review

The ISS, as the primary platform for current microgravity research, is a complex socio-technical system. It's performance depends upon complex interactions between institutions with evolving policy objectives and technical constraints to maintain its operation in LEO [29]. Complex technological systems can both create particular social orders depending on how the technology is arranged and enforce particular power systems based on technology requirements or compatability [30]. A common example is architectural exclusion [31]. Before the Americans with Disabilities Act was enacted, persons with disabilities were physically excluded from public spaces, simply by technical design of the buildings [30]. While in many cases this was due to long-standing neglect, in some cases such design has enforced discrimination, such as with low-pass bridge design in the Jim Crow era to physically exclude black and low-income communities from taking buses into public beaches (there are debates as to the degree of intention behind the design) [30, 31]. Apollo spacecraft were designed under the expectation that they would be piloted by military test pilots, limiting the early astronaut corps to only men. Even today, the continued use of ill-fitting suits, due to design and institutional funding issues, impacts the performance of smaller astronauts, who predominantly end up being female [32–35]. Wood and Weigel demonstrate that countries that participate more in space activities tend to have space-based infrastructure or launch capability [36]. Today that consists of the space agencies within the European Space Agency (ESA), NASA, Japan Aerospace Exploration Agency (JAXA), Indian Space Research Organization (ISRO), Russia, and China (although some other countries may be working on experimental launch capabilities). There is also evidence of many countries - some that could be characterized as developing nations, but not all - that do not have their own launch capability still investing in space participation particularly via satellite and science programs [36].

Opportunities for responsible innovation are presenting themselves within the evolution of a marketplace in the microgravity research ecosystem. Van den Hoven describes responsible innovation as "an activity or process which may give rise to previously unknown designs pertaining either to the physical world..., the conceptual world..., the institutional world (social and legal institutions, procedures, and organization) or combinations of these, which – when implemented – expand the set of relevant feasible options regarding solving a set of moral problems." [37]. Valdivia and Guston go a step further to extend responsible innovation in a policy context as a project to reform the governance of innovation that "seeks to to imbue in the actors of the innovation system a more robust sense of individual and collective responsibility." [38]. Responsible innovation can refer to products themselves or interal innovation practices to develop products. But it can also be applied to how we think of new designs of institutions or reforming the procedures and operations of a current one like the ISS. The European Commission discusses metrics of responsible innovation for industry and research in terms of gender equality, education, public engagement, ethics, open access, and governance. In the context of spaceflight and space systems, discussions on open access typically center upon reducing costs (launch and resource return) for commercial interests or maintaining redundancy for national security needs [39–41]. Economic theory also typically focuses on accessibility via terms like market penetration for sellers or willingness-to-pay for groups on the demand side. However theoretical frameworks and empirical evidence demonstrate that in some cases an emphasis on corporate social responsibility can both serve stakeholder interests and support a business case [**?**, 42–45]. The proliferation of emerging technologies also engenders a need to discuss ethics and responsibility in science overall [46–48] and space exploration [49–51]. Within the emerging marketplace for microgravity research in LEO, there is an opportunity to further explore the dimensions of accessibility for non-traditional user groups on the demand side and examine how interactions between market economics and regulatory procedures affect accessibility for these user groups.

4.3 Theoretical Framework

The microgravity research ecosystem is a complex socio-technical system within which the ISS exists. The technical development and use of platforms within the ecosystem are strongly influenced by social considerations that equal, and sometimes surpass, the technical concerns [52]. To analyze and interpret this ecosystem, system architecture methodology will be used. As Crawley, Cameron, and Selva propose, system architecture is "the embodiment of concept, the allocation of physical/informational function to the elements of form, and the definition of relationships among the elements and with the surrounding context" [53]. Key to this methodology are the principles of form-function relationships and emergence. Different entities of the system take on system forms to meet system functions aimed towards meeting stakeholder objectives. Functions can be met via several different forms; depending on intentional design or unintentional evolution. Stakeholders are the people, groups, and organizations that impact a system or are impacted by a system [**?**]. Understanding stakeholder needs and inputs to the systems depends on whether they are classified as primary and secondary stakeholders, whose decisions and outputs shape the system, or tertiary stakeholders (beneficiaries) whose needs are met by the outputs of the system [53]. The principle of emergence incorporates the idea that the functionality of these system entities and their relationships as a whole is greater than the sum of the individual entities [52, 53]. Understanding the context within which the system operates is also important, since context can be a source of uncertainty and risk. Context can be evaluated at different levels, such as international, national, and organizational, and can evolve beyond the control of individual system entities. Interpreting context is also useful for defining the boundaries of what the system is; such as, defining what falls under the spectrum of microgravity research [53]. In a technology oriented complex system, key areas of interpreting context include technology, policy, collaboration, and economics [54].

Drawing from systems architecture methodology work from Maier, Crawley, Wood, and Pfotenhauer [52–55], the microgravity ecosystem is analyzed using the six stages

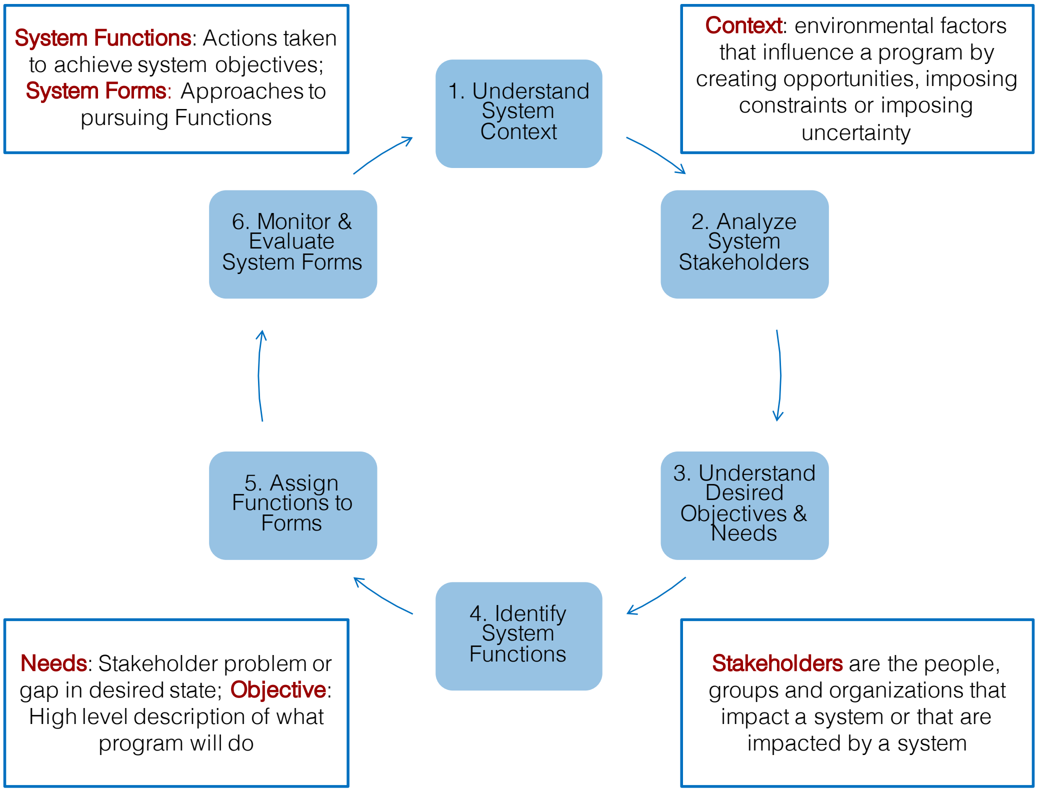


Figure 4-1: Systems Architecture Processes Utilized - Each stage of the cycle represents different questions that are asked to interpret and evaluate the microgravity research ecosystem. Image credit: Danielle Wood

outlined in Fig. 4-1. In defining the boundaries of the system, this analysis scopes the microgravity research ecosystem to research platforms within the LEO environment and below. Military-oriented platforms are not considered, but some of the stakeholder interests from this sector are briefly discussed. In order to evaluate the systems architecture, stakeholders, forms, and functions of the ecosystem, case study research methods are used to collect data. Publicly available information is reviewed about different entities in the ecosystem, the context they operate within, and their inter- and intra- relationships. Expert interviews were also conducted with organizational representatives, subject matter experts, and industry experts. All data presented and analyzed in the following chapters is current as of April 2019. The information and discussion presented are **non-exhaustive** of the entirety of the microgravity research ecosystem.

Understanding the system context requires understanding both the environmental factors in which different microgravity platforms operate in and the socio-political environment that influences different entities. As the discussion in Chapter 5 will demonstrate, the stakeholders of interest for this analysis, non-traditional partners and users of microgravity research, can be classified as secondary or tertiary stakeholders and beneficiaries. Therefore, to understand the desired outcomes and objectives of the system, the analysis seeks to evaluate the ecosystem in reference to the objectives of the beneficiaries instead of the primary stakeholders. In terms of granularity and scale to describe forms and functions, the analysis focuses not at an individual entity-based level but at a more abstract level. A key contribution of this theoretical analysis is describing the stakeholder models and using such models to help system users understand future paths. The systems architecture analysis describes different firms and entities in terms of models that they fit into, such as public space agencies and multi-use commercial platforms. To monitor and evaluate the systems metrics of accessibility are proposed and framework is utilized to evaluate current and future models of microgravity research against these metrics. The accessibility metrics are further described in Section 4.3.1.

4.3.1 Dimensions of Accessibility

Assessing levels of accessibility can be difficult if metrics do not capture the nuances of a particular complex system and the needs of the end users in the system. Prior work has analyzed the use of different cost- and distance-based accessibility metrics for online web content, health care systems, transportation networks, and food markets [56–59]. Today's microgravity research ecosystem has complexities that obscure what the actual costs are to the end user. Flight costs comprise a large portion of project costs, but sometimes these costs end up being covered by a public agency. Other development costs include prototyping the proof-of-concept for a project on the ground, developing the project to be flight ready and capable of withstanding hyper- and hypo-gravity levels, compatibility with the platform's power, communications, and data handling protocols, and coordination of how to manifest (install and uninstall) the project in a timely manner. Some of these development costs are financial but others are temporal and procedure oriented. Other regulatory costs could involve dealing with safety testing and certifications required by the platform supplier. Different types of platforms also allow for varying amounts of microgravity time and human-presence capabilities. For example current sub-orbital platforms do not allow for a human presence with the project payload, thereby limiting the type of projects to autonomous payloads and limiting the type of microgravity activity that can occur. Users may also face barriers depending on their nationality, the size and technical capabilities of their organization, and whether they are public, commercial, or non-profit oriented. For microgravity research, and the LEO space economy in general, there are no generally accepted and utilized metrics to evaluate accessibility for end users.

To capture these different nuances to accessibility in the microgravity research ecosystem, we propose metrics that can be used to rate current and future forms of access and designate whether they foster increased or decreased accessibility to new countries and organizations. This analysis proposes that accessibility can be assessed along the two dimensions of economic openness and administrative openness. Economic openness refers to the extent to which a future microgravity marketplace has high costs of access. This includes the costs to design an experiment; engineer it to be safe and functional; launching to space; accessing a facility that provides environmental control, data and power; operating the experiment; and possibly returning it to Earth. Administrative openness refers to the type of gatekeeping that determines who can participate, which may include access based on features such as nationality, type of organization, or type of microgravity activity. For example citizens from countries that are not ISS partners would need their own space agency to form a partnership with an ISS partner country or work through an international program. Also certain types of microgravity research platforms, like sub-orbital vehicles, do not currently allow for microgravity experiments that need a human operator. Such projects have to involve an autonomous experiment.

4.4 Spectrum of Microgravity Research Platforms

A microgravity environment is an environment in which gravity related phenomenon can be studied, assessed, and utilized. Microgravity research is not limited to just the ISS. Different terrestrial, sub-orbital, and orbital platforms provide microgravity environments to do research at different time scales. On the ground clinostats, drop towers, and parabolic flights simulate microgravity environments. Clinostats are typically used to rotate a cell culture or plant sample at different speeds to simulate microgravity along the axis (or axes) of rotation. However, rotation speed and incorporating multiple axes of rotation are difficult to optimize under the constraints of centrifugal forces and mechanical stresses on different types of samples. Drop towers consist of dropping samples vertically within the chamber of a tall tower or vertical shaft. Drop towers exist around the world and usually offer less than 5 seconds of microgravity time while an experiment is in free fall. Parabolic flights are typically operated in modified aircraft flying series of parabolas. At the apex of the parabola, the aircraft is in free fall, providing a microgravity environment for less than 30 seconds. Sounding rockets carrying experiment and instrument payloads to sub-orbital space, providing about 5-20 minutes of microgravity time before the payload re-enters the atmosphere. Experiment time depends on the rocket size, design, and launch profile. High-altitude balloons have also been used for microgravity research. A payload dropped at high altitude experiences free fall that can simulate microgravity for 3-30 seconds [60–62]. Orbital platforms can provide microgravity time for day to years. Platforms include research satellites, free-flying capsules, and space stations.

Chapter 5

Current Microgravity Research Ecosystem and Marketplace

5.1 Snapshot of the Current Ecosystem

This chapter presents an overview of the current stakeholders within the microgravity research ecosystem for platforms used for civil and commercial purposes within LEO. Data is collected using case study research methods [63]. Information presented is drawn off of publicly available documentation, current as of April 2019, and field interviews. Interviews were conducted with twenty individuals who were selected based on their experience as organizational representatives and industry subject matter experts in microgravity research. A sample of interview questions are included in Appendix D. All interviews were conducted with the approval of the Massachusetts Institute of Technology Committee on the Use of Humans as Experimental Subjects. A simplified Systems Architecture analysis of the stakeholders is demonstrated, highlighting what the stakeholders' needs and objectives are and the different pathways through which they interact with the microgravity ecosystem. Emphasis is placed on the different access points for customers and user groups on the demand side.

5.1.1 International Space Station

Since the arrival of Expedition One in 2000, the ISS has enabled continuous human presence in outer space. The size of a football field, the ISS orbits the Earth about every 90 minutes and offers opportunities for microgravity research, space exploration, technology demonstration, and international engagement. The ISS consists of two main sections - the Russian Orbital Segment (ROS) that is operated by Roscosmos and the U.S. Orbital Segment (USOS) that is operated by NASA, the Canadian Space Agency (CSA), ESA, and JAXA. Within the ROS, Roscosmos tends to maintain 2-3 cosmonauts and within the USOS, the partner agencies maintain 3-4 crew members [153]. The ISS is supported by ground facilities for launch, operations, and payload services in the United States, France, Netherlands, Germany, Russia, Kazakhstan, and Japan. Visiting crew and cargo vehicles (governmental and commercial) hail from Russia, Japan, and the United States [153]. In past years the ISS has played a role in Earth observation, commercial space economic development, STEM education and outreach, and research in human physiology, material science, and robotics [64].

Internal facilities and laboratories support long-term research in a microgravity environment and external research platforms enable testing in the extreme conditions of outer space. Research facility use and crew time allocations are dependent on the partner agency that provided the physical facility and crew time allocation agreements. According to Article 5 of the IGA, "each partner shall retain jurisdiction and control over the elements it registers and over personnel in or on the Space Station who are its nationals." [65]. The memorandums of understanding (MOUs) the U.S. signed with each of the partner agencies allocate more complex utilization allocations of USOS [66–68]. The allocation distributions for the ISS are shown in Figure 5-1. RSOS is under 100% Russian ownership and utilization, with the exception of the U.S. owned *Zarya* module. USOS is under mixed ownership and utilization [64, 66–68]. Partner agencies utilize their allocations for research in biology and biotechnology, earth and space science, human research, physical science, and technology demonstration [69].

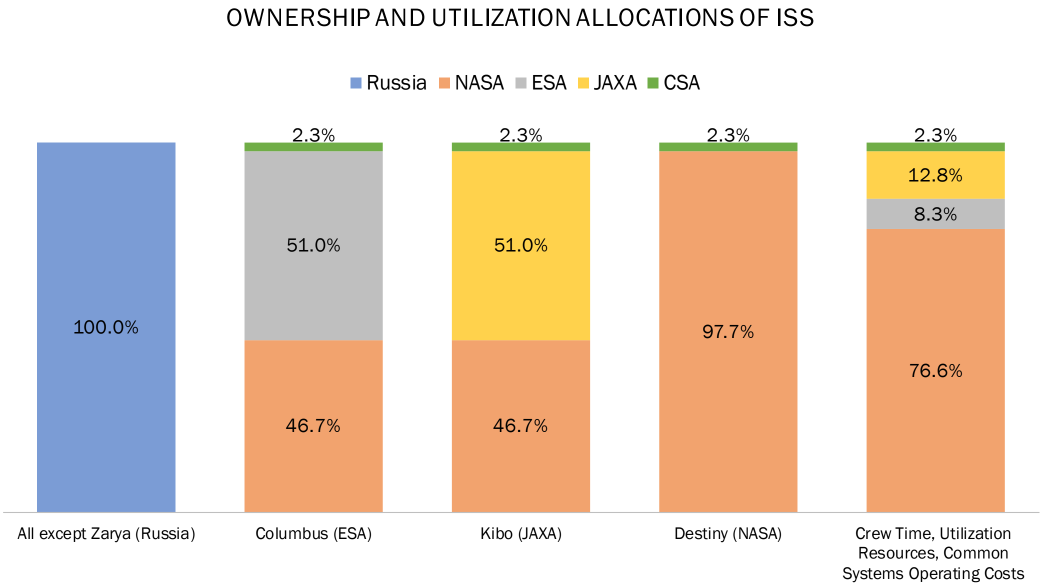


Figure 5-1: Ownership and utilization allocations of the ISS. With the exception of the U.S.-owned *Zarya* module, ROS is owned and utilized by Russia. *Columbus* was provided by ESA, *Kibo* was provided by JAXA, and *Destiny* was provided by NASA. The utilization allocations for these USOS modules are shown with NASA in orange, ESA in gray, JAXA in yellow and CSA in green. The allocations for logistical resources and costs are shown on the far right.

In 2005, the U.S. segment of the ISS was designated a National Laboratory to increase utilization of the lab by other federal entities and foster commercial interest in conducting ISS research. In 2010, the NASA Authorization Act directed NASA to work with a nonprofit organization to manage 50% of the Agency's available research resources on the ISS via a cooperative agreement notice [70]. In August 2011, NASA signed a cooperative agreement with the Center for the Advancement of Science in Space, Inc. (CASIS), and dedicated $15 million annually to manage all non-NASA research on the ISS [71–73]. The organization also refers to itself as the ISS U.S. National Laboratory (we will continue to refer to it as ISS National Lab in this document). Since 2011, the ISS National Lab has selected more than 200 non-NASA research projects from government, academic, non-profit, and commercial users. The projects range from the disciplines of life sciences, physical sciences, technology demonstration, remote sensing, and education [74]. For users from the startup community, the organization operates an investor network portal to connect investors with entrepreneurs involved with the ISS National Lab. In some situations, the ISS National Lab also operates as a funding entity. For science oriented project proposals, the principal investigator covers the costs for ground based prototyping. The ISS National Lab connects them with the implementation partners who quote the costs of integration services. Depending on the financial resources of the investigator team, the ISS National Lab may be able to cover some to all of the implementation partner costs [75]. Education projects are run through the Space Station Explorers, a consortium of educators, young learners, and education oriented partner organizations [76]. For projects that involve direct engagement with ISS experiments, some seed funding could be provided. Solicited proposals are evaluated based on the intellectual depth of the engagement and the number of learners reached. Emphasis is placed on projects that involve a more community-based approach where impacts can extend beyond just one cohort of students [77].

Beyond direct partner agency research and grants from the ISS National Lab, research on the ISS has also been facilitated by commercial partners. There are 14 commercially operated facilities on the ISS National Laboratory, managed by 8 commercial companies, and 45 implementation partners who provide commercial services to ISS National Laboratory users [78]. Some commercial firms have also entered into Space Act Agreements with NASA. These firms include Axiom Space, NanoRacks, Space Tango, Space Technology and Advanced Research Systems (STaARS), and TechShot [79].

For example, in 2009 NanoRacks signed a Space Act Agreement to self-fund their own research hardware and facilities as part of the U.S. National Lab and to market those facilities commercially [80,81]. The firm operates as an implementation partner with the ISS National Lab and also facilitates projects with its own users. The firm's products current include internal ISS payload platforms, satellite deployment from the ISS and Cygnus cargo vehicle, and the NanoRacks External Platform (NREP) mounted on the Japanese Experiment Module Exposed Facility. The firm also has a sister company, DreamUp, which operates as a public benefit corporation that offers space-based education programs to students and educators. Offerings include flying experiments up to the ISS and sub-oribtal space for primary to post-doctorate level students from different countries [82].

Space Tango operates automated research and manufacturing systems on Tango-Labs installed on the ISS since 2016. They offer end to end payload integration and data management services and focus on customer markets in the life sciences, physical sciences, flow chemistry, biomedical, and materials manufacturing [83]. Space Tango also has an agreement with the Quest Institute for Quality Education to host their engineering module upon which which students can learn to code experiments [84].

Through a partnership with ESA, the Belgian company Space Applications Services also offers the "plug-and-play" ICECubes experiment platform on the ISS *Columbus* module since 2018 [85–87]. The standard service supports experiment design, test, launch, and on-orbit operations. The firm has worked to launch payloads from the International Space University and European students via ESA's "Orbit Your Thesis!" program.

Projects from non-ISS partner agencies currently have limited options for direct access to ISS research. In this context, partner agencies essentially act as gatekeepers.

For organizations from countries that are not ISS partners, access to the ISS must be facilitated by a partner agency and the organization must work within the legal and logistical conditions set by the partner agency. For example, the ISS National Lab's portfolio of users is almost entirely U.S.-based. Organizations like the United Nations Office for Outer Space Affairs (UNOOSA) have facilitated agreements to broker access for non-spacefaring countries to conduct ISS research. The KiboCUBE program with JAXA aims to provide institutions from developing UN member state countries the opportunity to develop, manufacture, and deploy cube satellites from the ISS Kibo [88].

5.1.2 Other Microgravity Platforms

Beyond the ISS, other platforms currently available for microgravity research become more ground-based. Drop towers can be utilized to simulate extremely brief (less than 5 seconds) sessions of microgravity. UNOOSA is running its sixth cycle of partnership with the Center of Applied Space Technology and Microgravity (ZARM) in Bremen, Germany to offer student research teams from UN member states the opportunity to conduct experiments in the ZARM drop tower [89, 90].

Parabolic flight offers slightly longer microgravity sessions, the ability to simulate different gravity levels, and the capability of deploying a human-tended experiment without having to go to space. There are many military planes capable of flying parabolic maneuvers around the globe, but civil and commercial opportunities remain limited worldwide. In the U.S., Zero Gravity Corporation (ZERO-G) is the only commercial parabolic flight operator. The firm utilizes a modified Boeing 727 aircraft to offer parabolic flights for entertainment and research purposes to customers foreign and domestic. In Europe, Novespace - a subsidiary of the French space agency CNES - manages scientific flights on an Airbus A310 aircraft for space agencies, research groups, and occasionally entertainment customers [91]. In Russia, microgravity flights have been offered for entertainment purposes out of Star City in a Ilyushin 76 MDK jet that has been used for cosmonaut training [92].

Suborbital space also offers the capability of short-term microgravity research.

Blue Origin currently offers commercial, research, and education payloads slots on suborbital test flights of the New Shephard rocket. The project is currently under development for crew integration to extend capabilities for entertainment and human-tended experimentation [93]. Virgin Galactic also offers payload slots on suborbital test flights of it's piloted SpaceShipTwo system with in-house end-to-end payload integration [94]. High altitude balloons have also been used for short-term experiments, but the free fall state for payloads is difficult to control. Sounding rockets also offer the opportunity to fly payloads in extended, but not permanent, microgravity environments.

Microgravity research satellites have been developed to varying degrees around the world. China has launched research satellites with return sample capabilities and has collaborated with ESA in developing payloads [95, 96]. The Indian Space Research Organization (ISRO) has launched and recovered microgravity research satellites [97]. Commercial companies like SpacePharma also offer CubeSat platforms and integration services for automated pharmaceutical and medical device research [98].

The Chinese Tiangong program produced the Tiangong-1 and Tiangong-2 space stations which were utilized for crewed visits, microgravity research, and technology demonstration [99]. These stations were not permanently human-tended, but their construction enabled testing of docking procedures for future spacecraft planning. In April 2018, it was confirmed that Tiangong-1 re-entered Earth's atmosphere in an uncontrolled descent and the Chinese space agency has confirmed that Tiangong-2 will have a controlled de-orbit in July 2019 [100, 101].

5.2 Systems Architecture Analysis

5.2.1 System Context

As described in Section 4.3, the system context involves understanding the environmental factors that influence a program by creating opportunities, imposing constraints, or imposing uncertainty. Understanding the context also aids in defining the boundaries of the system to be analyzed. In this analysis, the microgravity research ecosystem is defined to include microgravity research platforms operating in LEO (less than 1000km in altitude) and below for non-military purposes. Launch services and small satellites are briefly considered as stakeholders and contextual influences. For example, recent increasing competitiveness in the launch industry, decreases in launch costs, and rideshare opportunities have reduced some of the costs and increased opportunities for transportation to orbit. The proliferation of small satellite technology and applications has resulted in a growing non-traditional user base of space technology, due to lower build costs and modularity of components.

For year, the ISS has operated as a unique orbital platform for microgravity research and a symbol for international cooperation. In recent years, private industry has also been affiliating with NASA and international partners to offer transportation, logistics management and payload demands. However, the ISS in its current operational form cannot be sustained forever. NASA has proposed ending direct federal funding of the ISS in 2025 and redirecting the the \$3-\$4 billion it yearly spends on ISS operations towards deep space exploration efforts [64]. As NASA looks towards commercialization of the low Earth orbit (LEO) space and the development of a cislunar station, concrete plans for shifting the public-private relationship of the ISS are unclear.

From different entities, there are many future proposals for public, public/private partnered, and private platforms on which microgravity research (which are described further in Section 6.1). Coupled with a possible increase from the demand side of microgravity research, a marketplace for microgravity seems to be emerging, which provides opportunities to reduce costs of access through competitive innovation [102]. However, the complexity and relationships between different public and private entities in the ecosystem also results in uncertainty as to what pathways non-traditional end users should pursue for access to microgravity research platforms.

5.2.2 System Stakeholder Analysis

Stakeholders to the microgravity research ecosystem can be classified as primary, secondary, and tertiary (beneficiaries) stakeholders. Primary stakeholders make decisions that can shape the ecosystem. Secondary stakeholders both make decisions to shape the ecosystem and influence the decisions of the primary stakeholders. Tertiary stakeholders, or beneficiaries, are impacted from functions and emergent properties of the ecosystem. In general, the impact to tertiary stakeholders may be positive or negative. The goal of the analysis is to identify functions that positively impact beneficiaries. Following analysis of public documentation and interview data, firms within the microgravity research ecosystem were identified into categories. These categories were then further classifed as primary, secondary, or tertiary stakeholders. The stakeholder categorizations are shown in Fig. 5-2. Stakeholders will continue to be referred to at the level of these categories instead of the firm-based level. While not always explicitly listed, it should be noted that some firms exhibit characteristics and functions of multiple stakeholder categories. A full analysis of stakeholder objectives, needs, and functions can be found in Appendix F. Following is a brief summarization of the stakeholders and their functions.

For the current microgravity ecosystem, primary stakeholders include critical suppliers of research platforms because their actions have physical and policy implications on whether and how microgravity research is possible. Critical suppliers of research platforms include the public space agencies that own the ISS, private parabolic and sub-orbital flight operators, and private facilities on-board the ISS. The ISS public space agencies maintain utilization of the ISS to achieve inter-governmental agreements and domestic agendas. Doing so requires clear priorities, public support, funding, and a competent workforce. Along each sector of the microgravity research spectrum, such as parabolic and sub-orbital space, the operators of flights to that altitude are also primary stakeholders. Through agreements with ISS space agencies, operators of private on-ISS facilities operate external and internal platforms on the ISS for customers. Some of these operators also work with public interfaces or take

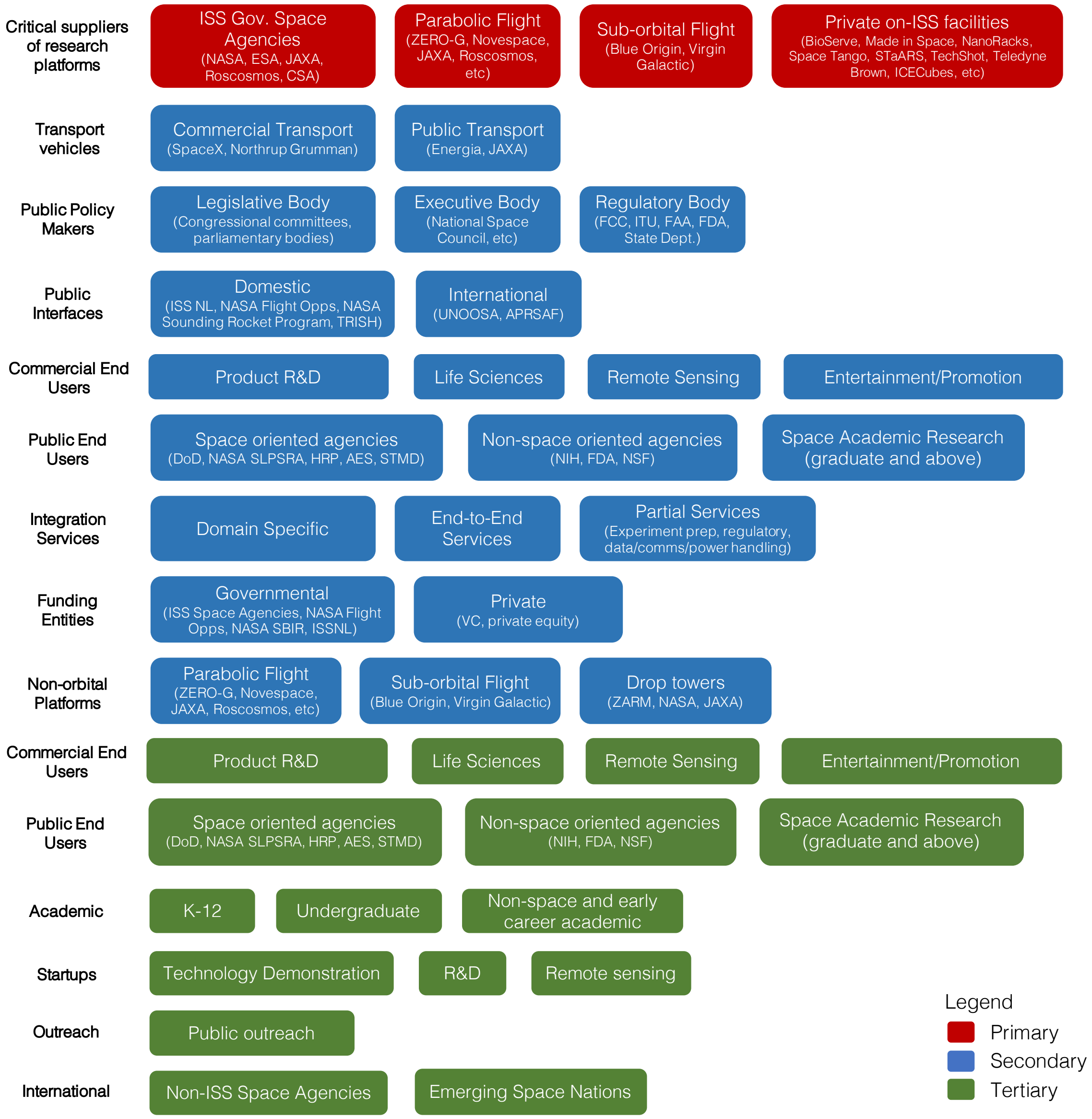


Figure 5-2: Stakeholder Categorization - Primary stakeholders are shown in red, secondary stakeholders in blue, and tertiary stakeholders in green.

on integration services roles as well.

Secondary stakeholders include transport vehicles, public policy makers, commercial end users, public end users, integration services, funding entities, and non-orbital platforms who all influence the decisions and operations of the primary stakeholders. Transport vehicles can be commercial or governmental vehicles (excluding the rocket upon which they are launched on). The capacity, re-entry capabilities, and environmental control systems of these vehicles influence the quantity and type of payloads that can be transported to orbital platforms. Public policy makers affect the ecosystem by appropriating funding of the ISS space agencies, setting domestic strategies, and regulating launch licenses and communications spectrum allocations. Examples include members of a congress or parliament (some individuals may hold more influence than others) or an executive body like the U.S. National Space Council (who are considering developing a National Microgravity Strategy) [103,104]. Public policy makers can also influence leglislation and enforcement of export control regulations (like ITAR restrictions on the type of projects or nationality of project personnel for the U.S.). Public interfaces are governmental or non-commercial entities that connect end-users with public, public-private, or completely private platforms. The process of connecting users could involve a solicitation call for projects, brokerage with technical experts at the interface firm or platform firm, upmass/down mass allocations, and occasionally some level of funding. Examples of public interfaces include the ISS National Lab, NASA Flight Opportunities Program, Translation Research Institute for Space Health (TRISH), UN Office for Outer Space Affairs (UNOOSA), and the Asia-Pacific Regional Space Agency Forum (APRSAF). Commercial end users execute projects and payloads on research platforms for product R & D and demonstration, life and physical sciences (including pharmaceuticals), remote sensing, and entertainment/promotion purposes. They work either directly with a platform supplier or through a public interface to execute projects on a platform. Public end users include space oriented agencies (including the ISS space agencies), non-space oriented agencies, and higher academic research. Different offices and divisions within NASA, such as the Division of Space Life and Physical Sciences Research and Applications (SLPSRA), the Human Research Program (HRP), Advanced Exploration Systems (AES), and the Space Technology Mission Directorate [64, 105] drive the research equipment needs and schedule of operations on the ISS. NASA also purchases parabolic flights from ZERO-G (during such flights, the ZERO-G aircraft is considered a government aircraft; for all other flights the aircraft is considered commercial) and payload space on sub-orbital Blue Origin flights. Non-space oriented agencies also execute projects and fund research teams to do microgravity research that aligns with their own missions, such as cancer or regenerative medicine research. Research at the graduate level and above tends to be publicly disseminated and sometimes funded by one of the other public agencies. Integration services are stakeholders that provide services such as experiment preparation, regulatory affairs assistance, certification tests, payload manifestation and return logistics, and data, communications, and power handling during flight. Some stakeholders provide domain specific services, such as for the biological sciences. Others provide end-to-end services that may be geared more towards end users who have never taken on a microgravity project before. Funding entities can be governmental or involve private financing. Depending on the stakeholder or which governmental funding source is used, different levels of intellectual property protections exist. Some public interfaces, integration services, and research platform suppliers also take on the functions of a funding entity. Non-orbital platforms providers such as drop tower, parabolic, and sub-orbital flight operators and are also secondary stakeholders in that they are often used as proving grounds to test the capabilities of orbital payloads.

In other systems, secondary stakeholders such as the public and commercial end users would typically be classifed as tertiary stakeholders since they benefit from the functions of the system. However, analysis of the microgravity research ecosystem demonstrates that such end users are also aptly classified as secondary stakeholders because they actively influence the suppliers that make up the primary stakeholders. Primary suppliers and other secondary stakeholders change their protocols and operations (now and in the past) to better meet the needs for public and commercial end users. This is particularly pertinent for early end users, or adopters, that are the first to go through the primary suppliers' processes. For some primary stakeholders, these end users help set the demand and value proposition for the suppliers to exist. Tertiary stakeholders, or beneficiaries, include the public and commercial end users along with non-traditional users of microgravity research. For the current ecosystem such non-traditional beneficiaries include emerging space nations, education groups (K-12, undergraduates), non-NASA and early career academics, startup firms, and public outreach groups.

General Observations and Findings of Current Ecosystem

Analysis of the stakeholders' objectives and functions within the current microgravity research ecosystem yielded some general findings that could potentially relate to accessibility.

- Emerging commercial marketplace
    - Investigating the existing private platforms and public-private partnerships demonstrates that there is an emerging commercial marketplace for microgravity research in LEO. In the past years there has been a growth in the number of private platform operators and private firms offering integration services. While some of these exchanges are dependent on public upmass/dowmass and resource allocations, such allocations could be viewed as utilization of public infrastructure that has already been paid for by taxpayers. Such public infrastructure involvement is not too different from how public road maintenance enables the safe transport of goods and services.
- Graduated approach to microgravity research
    - Comments from multiple interviewees and public documentation referred to a graduated approach to doing microgravity research, particularly for projects destined to an orbital platform. Whether the terminology called this raising Technology Readiness Levels (a common NASA term) or sim-

  ply testing out the compatibility of different technical subsystems, end users often tested projects aspects on parabolic and suborbital flights before manifesting it on an orbital platform. The availability of a continuum of platforms along the microgravity research spectrum can affect the development timelines of projects aimed towards orbital platforms.

- Regulatory burden
  - Regulations and and certification processes make up a significant portion of the activities required to execute a microgravity project. Regulations could involve launch licenses, communications spectrum allocations, ITAR/export control restrictions, and airspace clearances. Certifications involve multiple safety and compatibility tests specific to the type of platform. Public documentation and comments from platform operator interviewees support that firms are making regulatory affairs a priority in terms of legislative affairs, staffing, and operations procedures.
- Value of entertainment sector
  - Most private platform operators emphasize the importance of the space tourism and entertainment focused end users. While not included in as a stakeholder in terms of the microgravity *research* ecosystem, such end users could help make the business case for private platform operators and contribute to making overall prices low.
- Value of public interfaces
  - A majority of interviewees, from platform operators to end users, referenced the value of a public interface to gain access to a platform. The most commonly referenced interfaces were the ISS National Lab and the NASA Flight Opportunities Program. Some private platform operators expressed a desire to move beyond needing public interfaces to a more commercial interchange. However, currently public interfaces and the integration services they coordinate, are widely used.

- Barriers to founding and successfully operating a private platform
  - While high priority end users help set the demand and value proposition for private platforms to exist, the operator firms procure financial capital and take on the technical endeavor to develop the technology to build and operate their platforms. Many private platform firms were founded by entrepreneurs with enough personal funding to maintain early business viability. On some levels of the microgravity research spectrum, private firms also face market competition from a public or public-private partnered platform with different pricing mechanisms.
- Dependency on a competent workforce
  - Analysis of the needs for different stakeholders (Appendix F) demonstrated that many stakeholders need a competent workforce (in STEM and non-STEM fields) to develop and operate their platforms or services and maintain safe standards for passengers and research projects. Investment in STEM education and outreach programs (whether through a public or private mechanism) can also be viewed as an investment in a firm's future workforce.
- The ISS was built as a research platform
  - As reflected in the history of the ISS development (Appendix E), the ISS was planned, developed, and built as a research platform, not a platform to spur commercial utilization in LEO. For example, the equipment on the ISS is not currently purposed towards scaled manufacturing. However, current missions of public interfaces and statements from public policy-makers emphasize the importance of encouraging utilization from non-public end users and non-space oriented end users. While ISS equipment and docking ports have been adapted to better facilitate commercial utilization, this was not the original purpose of the ISS. The discussion in the next

chapter regarding proposals within the future ecosystem will highlight the importance of aligning platform purpose with utilization.

5.2.3 Forms of Accessibility

Systems forms are organizations, people, physical or virtual objects, programs and processes that execute functions [52,53]. Forms can also be transformed by functions. In systems architecture analysis, stakeholders allocate forms that execute functions to meet their own objectives. In analysis of accessibility within the microgravity research ecosystem, we focus particularly on what forms end users and tertiary stakeholders utilize to meet their objectives. These pathways, or forms of accessibility, are modelled in Fig. 5-3.

Based on example scenarios from the data analysis, pathways are categorized as purely governmental/public, mixed public/private, and fully private/commercial. The pathways express the processes and stakeholders that end users work through to place their research project on a microgravity research platform. From the end user, projects start out at the conceptual proposal stage. Through work on their own, or via a public interface and integration services, end users technically develop their projects to become compatible and/or flight ready for a platform. Finally the project is manifested (scheduled operation, allocated space and resources, and installed) on the platform. Different funding sources are involved for the pathway categories and for all pathways certain processes can be followed in reverse to return results or payloads back to the end users. All the pathways involving orbital platforms require upmass, downmass, and on-orbit resource allocations from a government, even the fully private/commercial pathway. In this sense, the government is providing transportation and logistics infrastructure for research and commerce to be conducted.

A purely governmental/public pathway utilizes public funding throughout the entire process. Public end users, particularly if they are from a division within an ISS space agency, have the option to directly manifest projects on a public platform due to technical familiarity of internal systems and processes. End users may also interact with a public interface program to coordinate with a public or privately operated

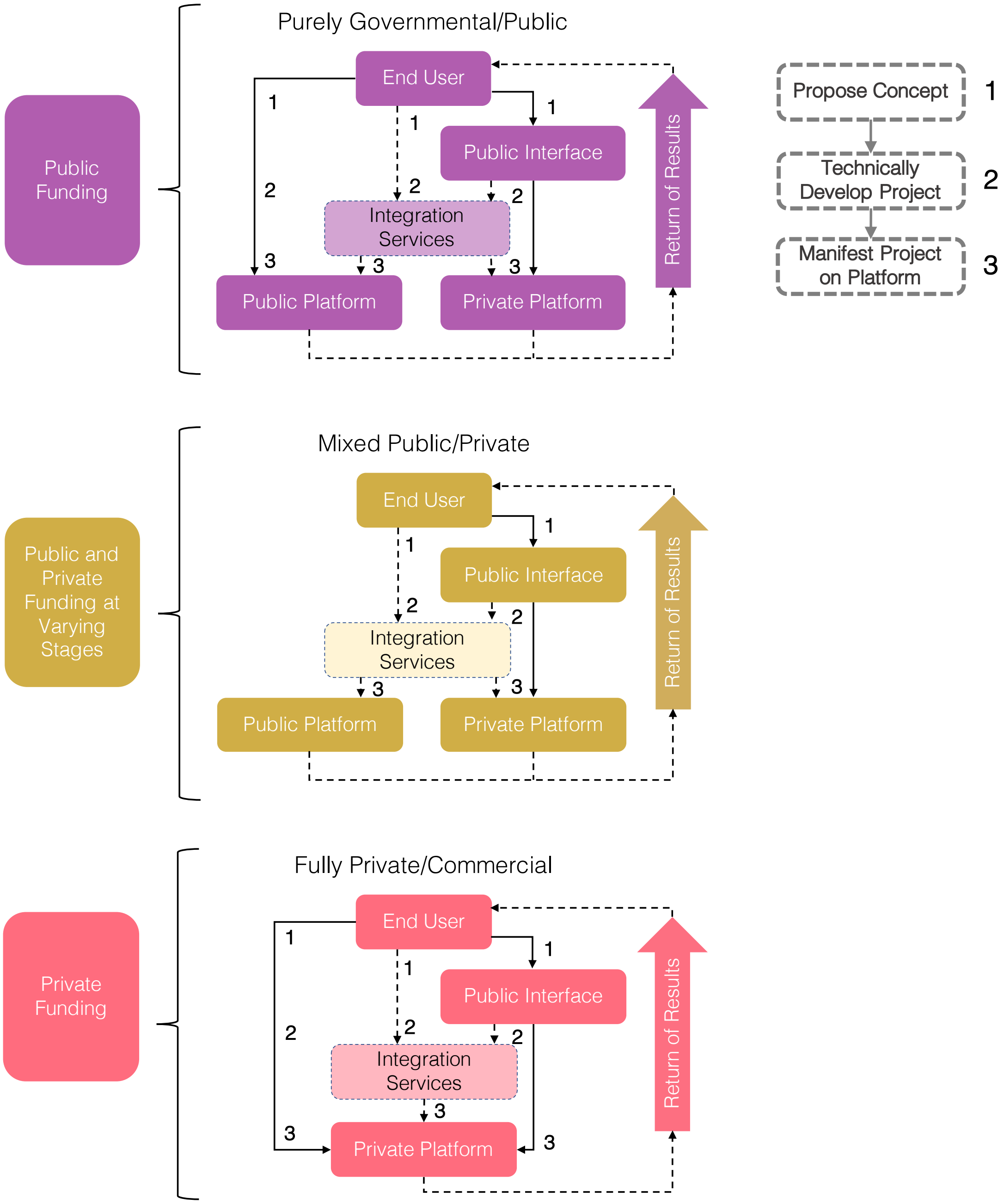


Figure 5-3: Forms of Accessibility - Pathways end users and beneficiaries utilize to meet their objectives in microgravity research. Forms can be categorized at Purely Governmental/Public, Mixed Public/Private, and Fully Private/Commercial. Along the pathway a project will move from the end user to the platform through a development chain. Along this chain, projects progress from the conceptual stage to technical development to manifestation on a platform. Almost all end users will seek results to be returned to the ground in some form. The rate of return can vary between pathway types.

platform. Depending on the technical familiarity of the end user, integration services may be utilized before a payload can be manifested on a platform. Since government funding is utilized throughout the pathway, there are limited intellectual property protections for the end user. Projects are also subject to governmental timelines and manifestation priorities. To receive funding, end user projects often must also be aligned with the needs of the governmental funding source.

Along a mixed public/private pathway, public and private funding sources are utilized at various stages, depending on the capabilities and needs of the stakeholder end user. For example, a mid-size commercial user may utilize public funding from a public interface for some integration services and rack space on a private platform, but also raise a portion of project funds privately to prototype on the ground. As shown in Fig. 5-4, if the private platform the commercial user chooses has in-house integration services, the user does not need to go through a separate integration services provider and may get access to the payload more quickly after flight. Or an education group may receive a combination of public funding to seed a project and a lower cost from a private platform due to their educational status and simpler project goals [85, 87]. End users go through a process similar to the that within the purely governmental/public pathway, with the exception of direct access to a public platform. Regarding intellectual property, protections can be dependent on the funding source and at what stage the funding is given. The project purpose doesn't necessarily have to be aligned with a government need, such as addressing a milestone in a strategy roadmap, but is more commonly aligned with a public interface objective, such as a biotechnology project or capacity building for an emerging space nation.

A fully private/commercial pathway utilizes private funding throughout all processes. An end user would raise their own funds, utilize funding from a private competition, or rely on philanthropy. Typically end users directly communicate and coordinate with the private platform operator, although depending on technical capability integration services may be utilized if they aren't already provided by the private platform operator. Some private platform operators may have their own agreements for on-ISS platforms and don't require coordination with a public interface. Other

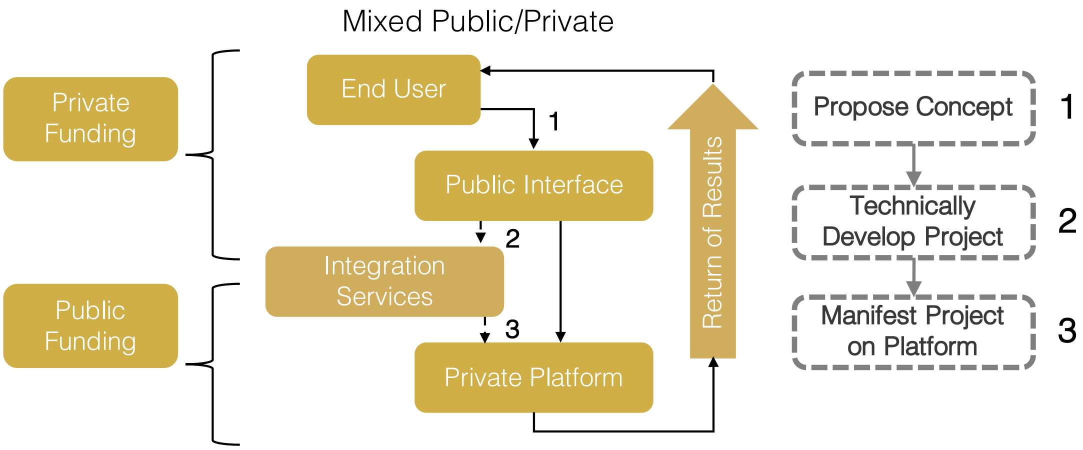


Figure 5-4: Mixed Public/Private Pathway Option - Detailed example of how a mixed public/private pathway may be utilized by a mid-size commercial end user who requires public funding for some amount of integration services and manifesting the project, but can prototype and do some of the technical development privately. The end user receives return of results via the integration services or directly from the private platform provider. If a public platform had been used instead, the end user would have wait for the government to do payload unloading.

end users may choose to utilize a public interface for coordination, but do not need public funding, or may choose a privately operated platform that requires coordination with a public interface. The fully private/commercial pathway provides a higher level of intellectual property protections due to being privately funded. End users projects don't necessarily have to align with a government mission or strategy, but they do need to comply with domestic regulations. In some instances for on-ISS private platforms, end user projects may need to demonstrate some type of relationship to benefiting humanity (ISS public space agency mission) or an education component.

5.2.4 Evaluate System Forms

To evaluate the levels of accessibility for these different pathways, or forms of access, we utilize the metrics of accessibility discussed in Section 4.3, specifically the dimensions of economic and administrative openness. By evaluating the pathways, we seek to investigate whether the pathways utilize responsible innovation in terms of governance processes and accessibility. Fig. 5-5 presents a framework upon which forms can be evaluated along the accessibility metrics. Forms can be mapped onto

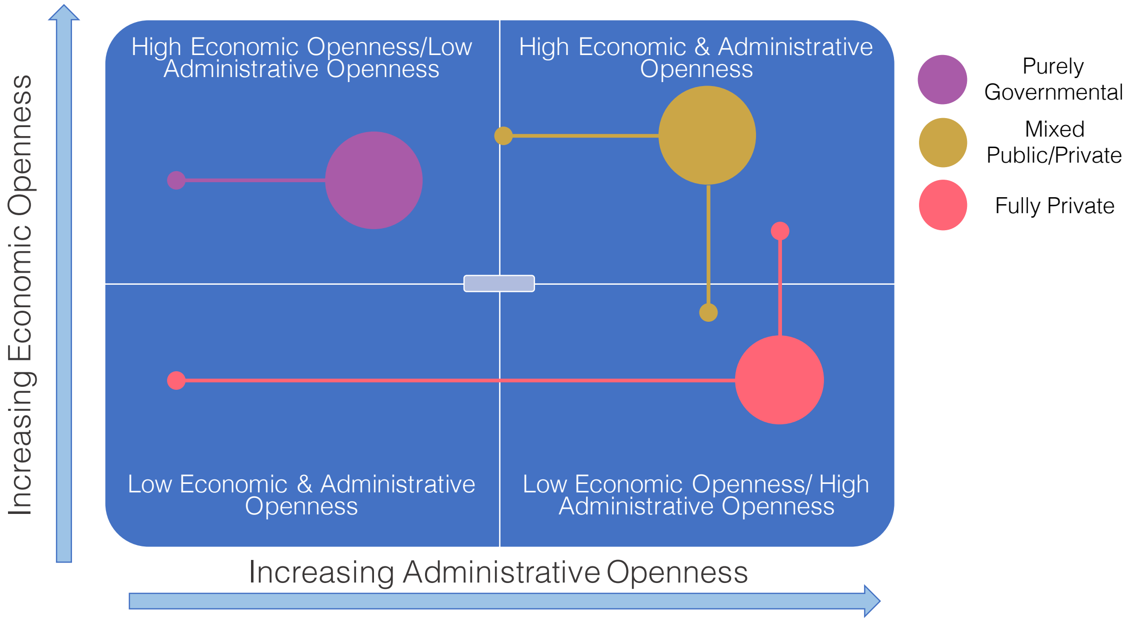


Figure 5-5: Evaluation of Current Forms of Access

different quadrants, depending on whether their characteristics and functions foster high or low economic and administrative openness. The different forms also have tails extending out along the axes. These tails visualize that there is a spectrum of openness within the forms themselves. Dependent on the end user, project purpose alignment, and type of final platform there is variability in levels of openness as well.

The purely governmental pathway has relatively moderate administrative and economic openness. This form of access is one of the primary modes of access end users currently utilize to gain access to a microgravity research platform. For example, the ISS is a multi-partner and multi-use facility. The ISS is a large scale, multi-purpose infrastructure that provides capabilities for a variety of activities. Some of these uses were anticipated during the early stages of developing the ISS, however, new opportunities and applications have been identified since ISS construction was completed. The modularity of the ISS and later standardization of its docking ports facilitates the introduction of new hardware and activities that were not envisioned in the original design. However it's level of administrative openness is variable and dependent on the nationality of the user. Users of the nationality of a public platform can receive public funding (which increases economic openness). Governments are incentivized to fund access for their own citizens; for those citizens there is a high level of economic openness. Through the purely governmental pathway, public funding also entails project alignment with strategic goals of the domestic government. In some cases, this could also limit the type of activity end users take on and thus also limit administrative openness.

The mixed public/private pathway has relatively high economic and administrative openness. The private platforms increase administrative openness if they allow participants from all nations; and the public/private partnerships provide a minimum level of economic openness if they do not charge high costs for participants from their nations. Administrative openness could be decreased if the public interface utilized has restrictions on the type of project or nationality of the end user. Economic openness could also be decreased dependent on the resources and technical capabilities of the end user and whether funding sources are available for integration services.

The fully private pathway currently provides relatively high administrative openness and relatively lower economic openness. Currently this pathway is smaller, or there are less methods and platforms to utilize this pathway by, relative to the other forms of access. On the administrative dimension, this pathway has high administrative openness because access is much less restrictive on the basis of nationality. However, this also means that without public funding, access is limited to those who can afford it or privately obtain funding, thus limiting economic openness. Economic openness can increase dependent on an end user's ability to obtain private funding or if they have the internal capacity to utilize less integration services. Administrative openness can decrease if the private platform is single purpose, limiting the type of project that can be manifest, or dependent on other domestic regulations.

5.2.5 Monitoring System Forms

Through systems architecture analysis methods, the current microgravity research ecosystem was categorized into the different stakeholder categories and forms of accessibility were identified and evaluated along the proposed metrics of accessibility.

Utilizing the systems architecture methods enables abstraction of the the complex socio-technical system presented in Section 5.1 and evaluation of the system functions that affect accessibility for end users. To continue to monitor accessibility of the ecosystem, in the next chapter we look towards how such methods and evaluation metrics can be applied towards the future microgravity research ecosystem.

Chapter 6

Future Microgravity Research Ecosystem and Accessibility

This chapter extends the prior discussion by analyzing what the future microgravity research ecosystem may look like. Based on information collected from interviews and public documentation, conferences, and meetings, we present a **non-exhaustive** snapshot of what the future ecosystem may look like. The systems architecture analysis is updated to reflect new stakeholder categorizations and changes in the forms of accessibility. These new pathways are again evaluated along the metrics of accessibility to measure how they might foster participation in microgravity research from non-traditional user groups.

6.1 Snapshot of the Future Ecosystem

6.1.1 ISS Operations

In the past decade, the operational life and U.S. directed funding for the ISS has been repeatedly extended. Currently NASA spends about \$3 - \$4 billion annually to maintain and support ISS operations [64]. The 2018 U.S. President's Budget Request proposed ending direct federal support of the ISS in 2025 with the goal of turning operations over to commercial entities and increasing growth in a commercial

Low Earth Orbit (LEO) economy [64, 106]. While the 2020 Budget Request for NASA no longer proposes an end date for federal funding, it does envision commercial capabilities on the ISS and new orbital commercial facilities in LEO [107]. The budget also requests $150 million to stimulate the commercial LEO economy and develop "a policy that outlines the specifics on commercial ISS usage and pricing and ensures that NASA or ISS National Laboratory activities do not compete with capabilities and services provided by commercial LEO destinations" [107]. Feasibility studies analyzing what such a commercial LEO economy would look like are currently underway, but it is likely to still involve government involvement as a customer to meet research needs [108–110]. The ISS hardware is currently certified until 2028, but it will eventually reach the end of its lifetime, and crew time will become increasingly allocated towards space station repairs and maintenance [64]. Beyond the technical issues involved, there are the social and logistical issues involved around ownership. While the U.S. does maintain a majority of the operations and resource utilization allocations for USOS, it does not own all the modules. ESA maintains ownership over the Columbus module and JAXA maintains ownership of the Kibo module, to which NanoRacks's NERP is attached. Additionally, CSA owns Canadarm 2, which has been essential for station construction, maintenance, and EVAs. Logistically, the IGA and MOUs the U.S. signed with partner agencies in 1998, have become more intricate as each partner agency has brought in agreements with their own partners via multilateral organizations like UNOOSA and commercial entities. In terms of overall strategy in LEO, within the U.S., NASA and the Departments of State and Commerce support human spaceflight goals of a continuous American presence in LEO, by NASA astronauts and private citizens, and expanding commercial opportunities through international engagement [111].

Symbolically, the ISS has been utilized as an emblem of international cooperation and human ingenuity by not just ISS partner agencies, but communities all around the world. The image of the ISS disintegrating towards Earth in de-orbit, controlled or otherwise, may not only symbolize a break in continuous human presence in space but also affect the sentiment of international cooperation. Embedding international cooperation at the beginning of the planning and life of the ISS offered it a layer of insulation from U.S. congressional cuts in the 1990s. Given recent statements from U.S. leadership about the motivation to maintain America's leadership in space, it's possible that international prestige may again play a role in determining the fate of U.S. involvement in the ISS. International engagement beyond just ISS partners could not only expand the marketplace for global space commerce, but also help ensure long term sustainability in LEO since more stakeholders will have a vested interest in keeping that commons space available for utilization.

6.1.2 Other Proposed Platforms

In the midst of this uncertainty among ISS partner agencies, non-ISS partners and commercial entities have begun to propose their own space stations. Some proposals depend on the ISS as a starting point, either through technology demonstration or as a docking point to begin construction of a new station. Bigelow Aerospace currently has its Bigelow Expandable Activity Modules (BEAM) attached to the space station as an expandable habitat technology demonstration for reducing transport volume for future space missions [112]. Based off of this technology, the firm has also proposed standalone space stations called B330s and announced a spinoff company to run its space station operations [113]. It envisions the B330s as fully autonomous space station capable of housing six crew members, docking with the ISS, and operating as a free flying commercial platform.

Russia has proposed the Orbital Piloted Assembly and Experiment Complex (OPSEK) as a third-generation modular space station in LEO. Since the ROS is still awaiting delivery of more Russian modules, including the Nauka laboratory, OPSEK could utilize these modules instead. Although OPSEK was initially proposed to be built off of current ROS elements once ISS retires, extensions of the ISS's operational lifetime have spurred discussions that OPSEK will be an entirely new station launched to a higher latitude that will enable Earth observation of Russia [114, 115]. Commentary by the Roscosmos head in 2017 also suggests that currently there are no plans to separate the ROS segments of the ISS and instead plans for future LEO stations should consider different management and investment structures to make it more efficient [116].

NanoRacks has proposed operating space station outposts by utilizing spent upper stages of rockets like ULA's Vulcan Centaur or the Space Launch System. The firm is part of NASA's NextSTEP effort to conduct a feasibility study and has proposed that its outposts could either attach to the ISS or be free-flying, using robotic technology to outfit the upper stages. NanoRacks currently has a customer base from its payload integration products and was recently awarded a grant from NASA to study the future of human spaceflight in LEO [117]. The firm also has a Space Act Agreement to develop and install Bishop commercial airlock, scheduled to launch in late 2019. The airlock has been privately financed, aims to increase deployment capacity, and will be launched by NASA [118, 119].

Axiom Space, led by veterans of NASA's ISS program, has proposed a space station made up of nodes and modules initially docked with the ISS. Modules include a habitation module, research and manufacturing module, and window observatory [120]. Launch of the system has been dependent on whether NASA awards the firm a dock to begin construction, after which funding rounds may continue [121]. However, recent public comments demonstrate the firm's plans to have private astronauts on the ISS in late 2020 and the Axiom segment operation by 2023 [122]. Additionally, frequent crew and cargo missions will maintain continuous human-tended operations to support the research themes of human research for exploration, life and physical sciences, space and earth sciences, commercial R & D, and STEAM education outreach [122].

In the late 2020s Space Tango also plans to launch the ST-42 as an uncrewed autonomous orbital platform [123, 124]. A free-flying platform (not docked with an existing platform), ST-42 will not require docking with the ISS or human-rated environmental controls, which may allow for freedom from NASA launch schedules and reduced overhead and time before customers can access their payloads [123, 125]. Following with some of the research focuses of the TangoLabs currently on the ISS, ST-42 seems to focus on manufacturing and biomedical applications, emphasizing compliance with FDA standards [124, 125].

Sierra Nevada Corporation (SNC) is developing the autonomous Dream Chaser craft for crew and cargo missions to LEO. SNC has an ISS cargo resupply contract for the Dream Chaser, with flights planned to start in 2021, but the vehicle is being designed to have an open architecture to allow for free-flying missions and compatibility with other future orbital platforms [126, 127]. The Dream Chaser is designed to launch from a rocket and complete a low-G runway re-entry. SNC emphasizes the craft's mission flexibility, data communications capabilities, and quick access to payloads upon different runways [126, 127].

For sub-orbital flights, both Blue Origin and Virgin Galactic plan on developing capabilities for human-tended payloads. While autonomous payload slots for these flights have been offered through the NASA Flight Opportunities Program, the regulatory landscape for NASA-sponsored human-tended research payloads is currently unclear and may involve input from the FAA's Commercial Space Transportation Office [128–131].

Airbus is also planning on installing its *Bartolomeo* platform external to the *Columbus* module through a partnership with ESA. With an unobstructed nadir view from the ISS, the firm plans to host larger payloads for applications like remote sensing, robotics, and physical sciences from public and private end users [132]. Airbus offers end-to-end integration services and has partnered with the ISS National Lab to operate as an implementation partner and offer platform usage [75, 133]. The firm has also partnered with UNOOSA to accommodate a payload from a UN member state, preferably a developing country [134].

The China Manned Space Agency (CMSA) plans to complete construction of its China Space Station by 2022 as a long-term habitable space station with multipurpose science research facilities [88, 135, 136]. CMSA has also partnered with UNOOSA to solicit applications to fly experiments on-board the planned China Space Station. Any UN member state may apply and the program has already received 42 applications from public and private entities in 27 countries, including the United States [137]. Designs for the China Space Station may have derived lessons learned from the Tiangong program and documentation from the UNOOSA solicitation detail station structure, experimental hardware, and proposals for basic configuration assembly by 2022 [135]. Additionally, UNOOSA has partnered with the Sierra Nevada Corporation (SNC) to fly experiment payloads oriented towards the Sustainable Development Goals on SNC's developing Dream Chaser space vehicle [138].

6.2 Systems Architecture Analysis

6.2.1 System Context

For the future microgravity research ecosystem, the boundaries of the system remain the same as the previous analysis to include microgravity research platforms operating in LEO and below for non-military purposes. With all the new proposals for platforms and changing operations, this results in the system growing, particularly in quantity of orbital platforms. However, there also changes in the socio-political and economic contexts for the future ecosystem.

The United States, ISS partner countries, and China have shown increasing interest in fostering a commercial LEO economy for strategic reasons. Economically it is beneficial for these countries to foster new marketplaces and economic growth. If a commercial provider can effective meet the public end user needs, the public agencies can re-direct funds from operating their own platforms to other efforts. A global commercial LEO marketplace could also expand the customer base and increase international cooperation engagements. The private sector is also interested in developing a commercial LEO economy, particularly on the supply of microgravity platforms. However, some of the main uncertainties for public agencies and private entities are whether there's enough demand from non-public end users and whether a future LEO economy can support the number of platform suppliers that have been proposed. On the demand side for microgravity research, one of the main concerns from all end user types is the rate of return on payloads and experiments. Rate of return is affected by the policies and procedures of the platform provider, any public interface or integration services utilized, and compatibility with different launch service providers to meet launch frequency needs.

Governmental focus on fostering accessibility seems to be focused on commercial end users, including startups, but not very oriented towards other non-traditional partners. In fact when prompted with research goals of evaluating accessibility for non-traditional partners, most interviewees initially took this to mean startup companies or the just the non-space oriented commercial sector. When further prompted that in this analysis non-traditional partners include education outreach groups and emerging space nations, some interviewees pointed out that if a commercial LEO economy is allowed to grow on both the supply and demand side, overall prices could be reduced which may decrease some of the cost barriers for non-traditional partners. While this may or may not result in the future, most of the intentional public policies and private platforms are being developed to serve the demands of the commercial sector and not all non-traditional partners.

While national security based platforms are not considered in the system, national security concerns do affect the political context of the microgravity research ecosystem. During the development of the ISS, national security concerns influenced how international partners were brought onto the project and the motivations behind bringing Russia on as a partner. Today the United States has experienced increasing political tension with China and NASA is legislatively barred from federally funding any bilateral projects with China. Meanwhile, China has cooperated with almost every major public space agency, except NASA, on projects [137]. Increasing the number of overall international partnerships could not only increase security through alliance building, but also help ensure sustainability in LEO as more countries will have a stake in keeping it open and operable for a marketplace and research ecosystem.

6.2.2 System Stakeholder Analysis

The stakeholders are again identified and categorized into primary, secondary, and tertiary stakeholders, which are shown in Fig. 6-1. Most of the stakeholder categorizations remain the same. The current stakeholders are still present since none have publicly announced or authorized plans to completely withdraw from operations. While several of the ISS public agencies have publicly discussed a desire to re-direct funding efforts away from ISS and allow the private sector to provide more services, they have yet to stop authorizing involvement with the ISS and still maintain multiple public-private partnerships regarding launch services and private on-ISS facilities.

The biggest change is seen in the number of stakeholders operating as critical suppliers of research platforms. Additional categories now include single government, multi-partner, private ISS docked, and private orbital free flying. Single government represents space station proposals where the current design is wholly owned by single government like the China Space Station or Russian OPSEK. The multi-partner categorization encompasses the current ISS public agencies (from Fig. 5-2). If one of the single government platform designs evolved to include ownership of a module by another country, the platform may be re-designated as multi-partner. Private ISS docked refers to private orbital platforms for which the public designs currently rely on docking with the ISS for initial construction. Private orbital free flying platforms don't necessarily need to dock with the ISS, but may have the capability of docking with their own modules to become more complex or docking with another orbital platform. Many of the private platform operators on the ISS or otherwise also aim to provide integration services as part of their operations.

Similar to the current ecosystem, these end users are tertiary stakeholders because they benefit as end users from being able to perform microgravity research on platforms and secondary stakeholders because they influence how some of the platform suppliers design policies and procedures. For the future ecosystem, commercial and public end users (particularly early adopters) strongly influence the primary stakeholders as many of the future platform proposals are specifically designed to meet those end user needs. For example Space Tango's ST-42 proposal is oriented towards mission specific research and materials manufacturing goals. The firm is already taking into account FDA regulations on production processes to meet the needs of possible pharmaceutical customers [124, 125]. At least from public documentation and commentary, Axiom's space station designs seem to have evolved from hotel and

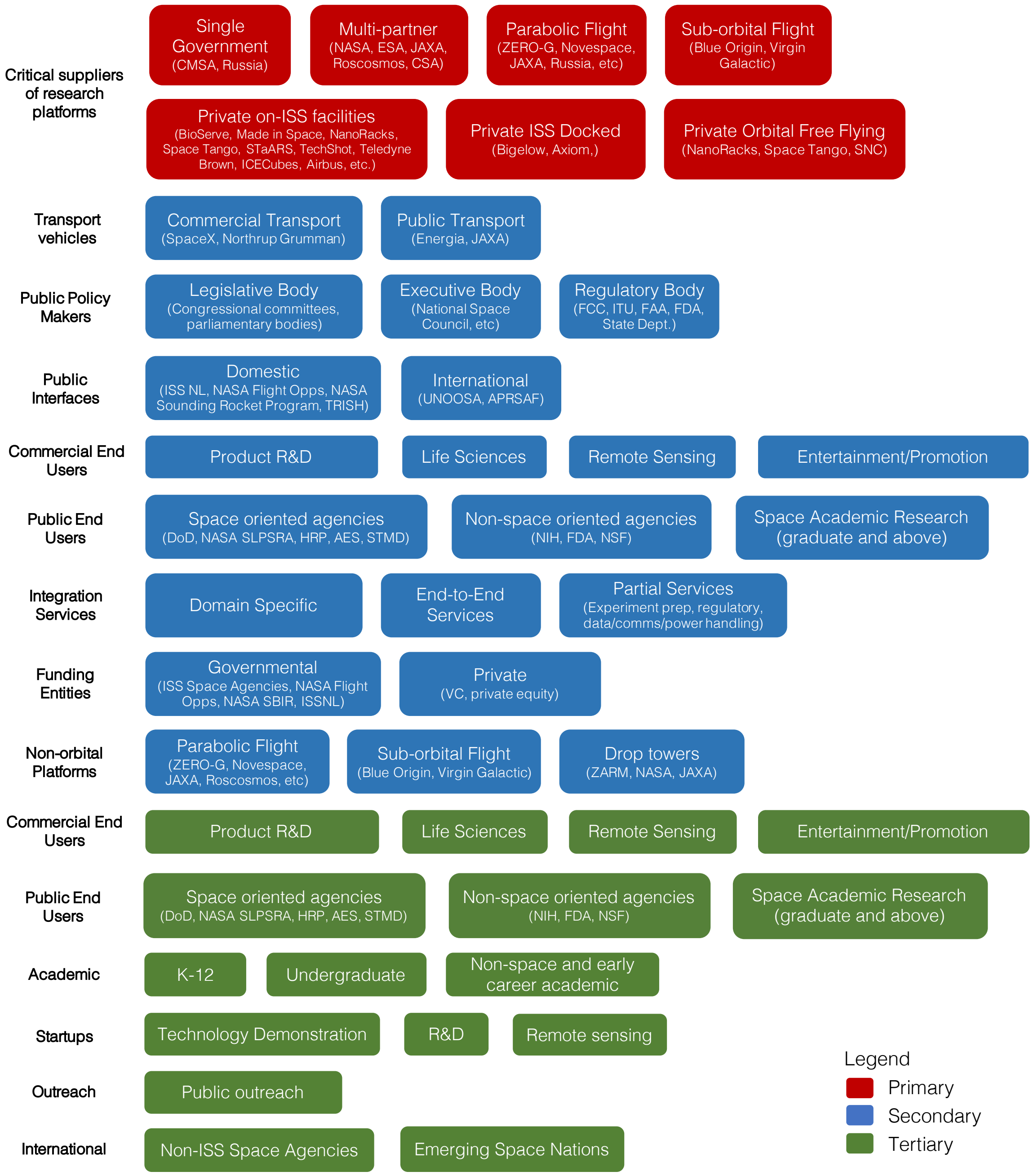


Figure 6-1: Future Stakeholder Categorization - Primary stakeholders are shown in red, secondary stakeholders in blue, and tertiary stakeholders in green.

entertainment services to also having modules purposed towards research and manufacturing and extending the overall capacity of the ISS [120, 122]. Looking at a broader scale in analysis, public comments from space agency officials and interviewees reflect that the demand for microgravity research from these types of end users is one of the biggest uncertainties and barriers to having a sustainable commercial marketplace in LEO with minimal government involvement [109, 139].

6.2.3 Forms of Accessibility

The forms of accessibility discussed in the last chapter (Fig. 5-3) largely remain the same and are repeated in Fig. 6-2 below for clarity. As the future microgravity research ecosystem currently stands, forms of access, or pathways, can still be categorized as purely governmental/public, mixed public/private, and fully private/commercial. Funding-wise, there may be a larger number of private funding entities with interest in financing microgravity research projects for the private sector [140]. While there is projected to be an increase in the number of orbital platforms, this does not necessarily change the pathways end users will utilize to develop their project. What may change is whether end users have to utilize distinct public interfaces or integration services within the pathway, since more platform providers are proposing to offer in-house integration services. The speed by which an end user can progress through the pathways may also increase due to increased launch frequency and the freedom free flying platforms have from ISS schedules. The relative size of the mixed public/private and fully private/commercial pathways is also projected to increase due to an increase in the number of private platform operators and the reliance of some on public-private partnerships. It's possible that mixed public/private and fully private/commercial pathways will involve reduced costs for end users, but this is largely dependent on the amount of future demand.

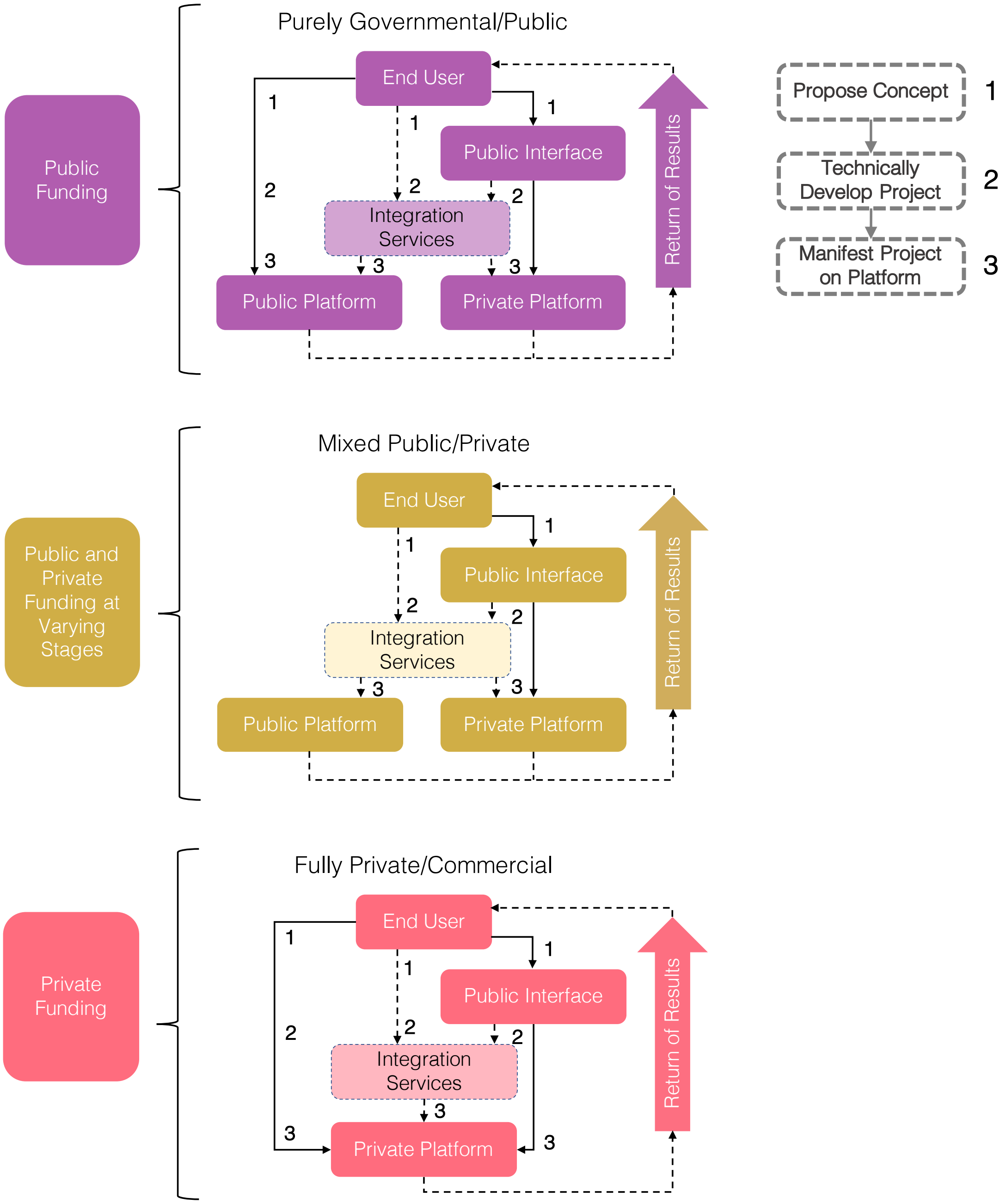


Figure 6-2: Forms of Accessibility - Pathways end users and beneficiaries utilize to meet their objectives in microgravity research. Forms can be categorized at Purely Governmental/Public, Mixed Public/Private, and Fully Private/Commercial. Along the pathway a project will move from the end user to the platform through a development chain. Along this chain, projects progress from the conceptual stage to technical development to manifestation on a platform. Almost all end users will seek results to be returned to the ground in some form. The rate of return can vary between pathway types.

6.2.4 Evaluate System Forms

The metrics of accessibility are again utilized to evaluate the future forms of access. Fig. 6-3 presents the different pathways evaluated for economic and administrative openness. The pathways are mapped onto the quadrants that align with how that pathway fosters openness. Tails extend out from the pathway circles to capture the variability and nuance within the pathways. The size of the circles represent the gross amount of methods for end users to utilize that pathway relative to each other.

In contrast to the previous analysis, the purely governmental pathway is split into single government and multi-partner governmental to distinguish the differences in administrative openness between the two types of platform providers that could be involved. A multi-partner governmental pathway (2) mostly closely resembles the purely governmental pathway in the previous analysis. This pathway has relatively high economic openness, but only by working through one of the governmental pathways or being a citizen of one of those governments. Administrative openness can also decrease depending on internal government funding mechanisms, processes, and schedules. A single governmental pathway resembles the pathway that would be taken to use a public platform like the China Space Station or Russian OPSEK. Administrative openness is further decreased in this pathway since just one government acts as a gatekeeper for access. For a platform like the China Space Station which has a partnership with UNOOSA and has desires to cooperate with other space agencies, administrative openness could increase.

The mixed public/private pathways has relatively high economic and administrative openness. This pathways has characteristics similar to that in the previous analysis. Administrative openness is increased relative to the governmental pathways since there would be more flexibility on the nationality of an end user developing the project and end users would not be restricted to as strict government schedules and procedures. Additionally for future sub-orbital and orbital platforms, it is assumed that the platforms will have increased capabilities for a human presence. If a private platform is involved, there could be less restrictions on the nationality of the private astronaut by avoiding government ITAR and export control restrictions. However depending on the nature of the public-private partnerships made, administrative openness could also decrease dependent on the portion of public funding used and if the public platform is utilized. Economic openness could also decrease depending on the capabilities of the end user, previous experience with microgravity research, and fund raising opportunities from public and private entities. The most significant change from the previous analysis is the size of this pathway. A majority of the proposals for future platforms either currently utilize a public-private partnership or rely on docking with the ISS. For the proposals that have current operations, many of their science and education related payloads utilize some level of funding and coordination from a public interface. Relative to the other pathways, the mixed public-private pathway may be more likely to be utilized by end users in the future.

Also similarly to the previous analysis, the fully private/commercial pathway has relatively high administrative openness and low economic openness. This pathway would have more administrative openness than the mixed public/private pathway since it would not be bound by any governmental schedules or procedures and possibly less export control. However, this pathway could also vary to low economic openness if the private platforms only served specific types of payload projects. While this pathway could be open to any type of end user, it is also only open to any type of end user that can afford it. But in contrast to the previous analysis, the fully private pathway could also vary to have high economic openness. If there is enough demand present to foster a competitive marketplace, it's possible that prices could decrease for all types of end users, thereby increasing economic openness.

6.3 Conclusions

To assess accessibility in the microgravity research ecosystem for non-traditional partners (startups, non-NASA and early career academics, emerging space nations, and education outreach groups), metrics of economic and administrative openness were proposed. Systems architecture methods were utilized to analyze the stakeholders,

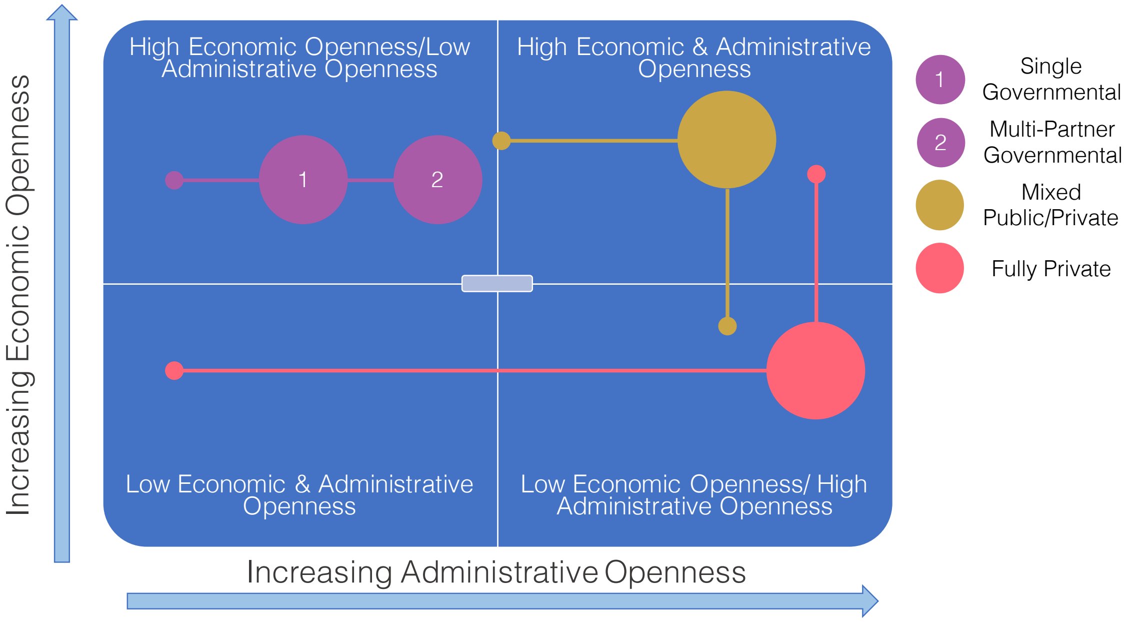


Figure 6-3: Evaluation of Future Forms of Access

functions, and forms that emerge in the ecosystem to meet different stakeholder objectives. From this analysis, general findings about the research ecosystem were observed and different forms of access, or pathways were identified. Using the accessibility metrics these pathways were evaluated for whether their characteristics engender openness. The evaluation found that different public, public/private, and private pathways exist for different types of end users to gain access to microgravity research platforms. For now and the near future, mixed public/private pathways seem to foster relatively high economic and administrative openness. There exists future opportunities for private pathways to reach this same level of accessibility, but as proposals stand now, this is could be dependent on whether private funding opportunities, such as philanthropic programs, exist for non-traditional users to use for funding. Otherwise, some level of public funding is needed to interface with non-traditional partners, provide them the resources to use some level of integration services, and manifest their projects. Both primary stakeholders and public interfaces can also increase awareness of the pathways that do currently exist. Often, public documentation of successful projects from non-traditional partners failed to simply list the public interfaces, funding mechanisms, and partnerships involved to make the project successful. Better dissemination of such information about the different entry points end users can use to enter a pathway can lead to more utilization.

Even though many interviewees took the phrase “non-traditional partners” to only refer to commercial end users or non-space oriented public agencies, almost all recognized the importance of maintaining pathways for STEM education and outreach groups. Whether it be to meet a public agency mission, grow a future STEM workforce, or simply demonstrate corporate social responsibility, there appears to be some level of commitment among stakeholders to maintain and foster pathways for these user groups. For emerging space nations many economic barriers to access still exist; however, public interfaces and public-private partnerships offer opportunities to foster administrative openness.

The metrics of economic and administrative openness were proposed to capture different aspects of accessibility in the microgravity research marketplace. Using systems architecture methods, the metrics were used to analyze forms of access, but the metrics can also be utilized to evaluate the systems at a lower or higher scale. For example, previous work utilized the metrics to analyze research platform suppliers themselves and the overall marketplace [141]. However the metrics don’t necessarily reflect some of the more nuanced and temporal based changes in pathways from the current to future ecosystem. Future opportunities exist to either refine the forms of access identified or add more dimensions to the accessibility metrics. Such other dimensions could include the amount of time it takes for an end user to execute a project or the level of technical openness for an inexperienced end user.

The ISS and other current microgravity platforms provide a variety of research opportunities for user bases across the world. In the midst of discussions about how this ecosystem might change in the future, there have been a variety of proposals from commercial and governmental organizations for future microgravity platforms. As this complex ecosystem continues to evolve, assessing whether the emergent pathways of access actually align with the needs and objectives of end user groups is critical to optimizing the research ecosystem. Primary stakeholders and public policy makers can utilize the stakeholder categories, forms of access, and accessibility metrics as a common reference to analyze and evaluate microgravity research. Analyzing the current and future accessibility of the microgravity research ecosystem is not only ethically important, but also critical to inspiring and educating future generations. Furthermore, accessibility to communities across the globe can engender international cooperation for a global marketplace and for future space endeavors that no one country could accomplish on its own. The “spaces in space” that we operate in are evolving dramatically. Thinking about accessibility now is important to help ensure it for the future of all humankind.

Chapter 7

Conclusion

7.1 Research Summary

This thesis investigated the utilization of new metrics for studying human-machine interfaces and systems at a micro and macro scale. At the micro scale, we investigated how humans may strategize to move their bodies in order to complete a agility-based running tasks. For a slalom course, an optimal control model was formulated to analyze the characteristics of an optimal path trajectory to complete the task as quickly as possible. Opportunities to improve the model were informed by the utilization of a "micro" system - wearable IMU devices. While the path trajectories estimated from these devices have limitations, IMUs offer opportunities to measure human movement in natural operation environments, instead of a controlled laboratory setting. In the context of space exploration, such natural environments could also include planetary surfaces with reduced gravity. To evaluate how locomotion might change in such conditions, the optimal control model was used to investigate how an optimal path trajectory would change while completing the slalom task in reduced gravity. The results demonstrated that as gravity decreased, it would take a human more time to complete the task and the curvature about turning regions would decrease (wider turns). The results and limitations of the model in nominal and reduced gravity conditions demonstrated the strong influences gravity and ground reaction forces have on the path trajectories humans can execute.

Investigating some of the limitations of the optimal models depended on having experimental trajectories estimated from the IMUs as a platform of measurement. But the positional trajectory estimates from the IMUs are also limited due to drift error. Reflecting on how the curvature of the path trajectories decreased as gravity decreased, the metric of integrated curvature was proposed for analyzing the path trajectories of humans completing an agility task. The feasibility of using this metric was analyzed via a pilot study of another agility-based running task. Along with other common metrics of characterizing agility and path trajectories (task completion time and path length), the integrated curvature metric was evaluated using both optical motion capture and wearable IMU measurement platforms. The pilot study results demonstrated that subject performance in terms of completion time, path length, and integrated curvature could depend on whether a subject had *a priori* knowledge of the task goal and the structure of the task. While there may be some differences between the magnitude of the motion capture-based and IMU-based integrated curvature, these differences could be dependent on how the trajectories are smoothed and how subjects stutter step right before being cued to their task goal. Furthermore, the results demonstrate that there are opportunities to leverage the integrated curvature metric via the wearable IMU measurement platform to make decision-making conclusions.

Wearable IMUs offer a measurement platform that could be utilized in natural field settings, including reduced gravity planetary environments. But in order to test out and improve metrics for IMUs in these conditions, we require access to reduced gravity research platforms. Accessibility to microgravity platforms is complex and dependent on a variety of factors beyond just financial costs. And just as it is important to use human performance measurement platforms and metrics that can be leveraged in different operational environments for generalized user populations, it also important that access to microgravity research platforms is available for non-traditional partners. Non-traditional partners include users like startups, non-NASA and early career academics, emerging space nations, and education outreach groups.

In order to capture the complexities and nuances behind accessibility for end users in the microgravity research ecosystem, new metrics of economic openness and administrative openness were proposed. The current and future microgravity research ecosystems were surveyed using case study research methods. Systems architecture methods were utilized to analyze the stakeholders and forms of access (pathways) present in the ecosystem. The pathways were then evaluated using the new accessibility metrics. Analysis demonstrated that mixed public/private pathways can foster relatively high economic and administrative openness, but these levels of openness can decrease dependent on the capabilities and type of the end user and the type of funding sources used at different stages of the pathway. Opportunities exist to refine the accessibility metrics and add new dimensions of analysis. Whether it be for a technology at the micro-scale, like wearable devices, or at the macro-scale for a large complex ecosystem, like microgravity research, by refining metrics and examining platforms now, we can help ensure accessibility to these systems for any type of user in the future.

Appendix A

State Dynamics and Derivation of Ground Reaction Force Constraint

The following derivation is included in prior work [142] and is utilized in formulating the optimal control model in Chapter 2. The ground reaction force constraint was derived with assistance from Dr. Noel Perkins (co-author on [142]).

The state dynamics of the agility run optimal control problem extended from the method used by Flash and Hogan [5] are defined as follows:

$$\begin{aligned} x'(t) &= v_x(t) \\ y'(t) &= v_y(t) \\ v_x'(t) &= a_x(t) \\ v_y'(t) &= a_y(t) \\ a_x'(t) &= j_x(t) \\ a_y'(t) &= j_y(t) \end{aligned} \tag{A.1}$$

In evaluating how a subject running an agility run task minimizes time, one hypothesis would be that they can minimize time if they can maximize the horizontal ground reactions on their feet. That is, they can reach the finish line faster if they can generate greater accelerations (both on the turns as well as the straightaways). However, there is also an upper limit to those ground reactions as determined by the available traction between the ground and their shoes.

Here the subject is simply modelled as a particle (say mass m) subject to horizontal ground reactions both tangential and normal to the particle path. Newton's law is

$$\vec{F} = F_t \hat{e}_t + F_n \hat{e}_n = m\Big(\frac{dv}{dt}\hat{e}_t + \frac{v^2}{\rho}\hat{e}_n\Big) \tag{A.2}$$

where (F_t, F_n) are the components of the horizontal ground reactions tangential and normal to the path defined by the unit vectors $(\hat{e}_t, \hat{e}_n)$, v is the instantaneous speed, and ρ is the instantaneous radius of curvature of the path. If we further assume that the resulting horizontal ground reaction is bounded by the friction limit, then

$$\sqrt{F_t^2, F_n^2} = m\sqrt{\Big[\frac{dv}{dt}\Big]^2 + \Big[\frac{v(t)^2}{\rho}\Big]^2} \leq \mu m g \tag{A.3}$$

where μ denotes some effective coefficient of friction.
By simplifying Equation A.2, the ground reaction force constraint reduces to

$$\Big[\frac{dv}{dt}\Big]^2 + \Big[\frac{v(t)^2}{\rho}\Big]^2 \leq (\mu g)^2 \tag{A.4}$$

where

$$v(t) = \sqrt{x\prime(t)^2 + y\prime(t)^2} \tag{A.5}$$

and

$$\rho = \frac{[x'(t)^2 + y'(t)^2]^{\frac{3}{2}}}{x'(t)y''(t) - y'(t)x''(t)} \tag{A.6}$$

For nominal conditions

$$\begin{aligned} g &= 9.8\frac{m}{s^2} \\ \mu &= 0.45 \end{aligned} \tag{A.7}$$

For martian gravity

$$g = 3.71\frac{m}{s^2} \tag{A.8}$$

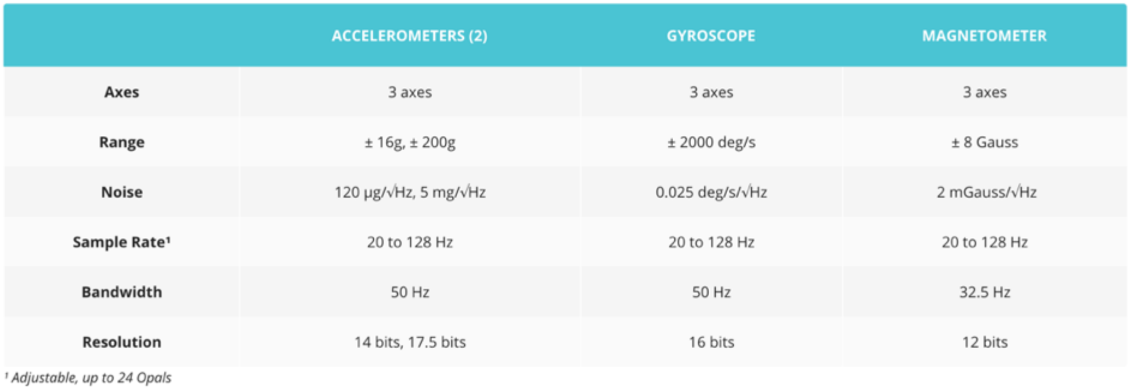
For lunar gravity

$$g = 1.622\frac{m}{s^2} \tag{A.9}$$

Appendix B

IMU Device Characteristics

B.1 Device Specifications



	ACCELEROMETERS (2)	GYROSCOPE	MAGNETOMETER
Axes	3 axes	3 axes	3 axes
Range	± 16g, ± 200g	± 2000 deg/s	± 8 Gauss
Noise	120 µg/√Hz, 5 mg/√Hz	0.025 deg/s/√Hz	2 mGauss/√Hz
Sample Rate[1]	20 to 128 Hz	20 to 128 Hz	20 to 128 Hz
Bandwidth	50 Hz	50 Hz	32.5 Hz
Resolution	14 bits, 17.5 bits	16 bits	12 bits

[1] *Adjustable, up to 24 Opals*

Figure B-1: Sensor Characteristics of IMUs. Devices are APDM Opal wearable devices, version 2.

B.2 Vicon Marker Plate Design

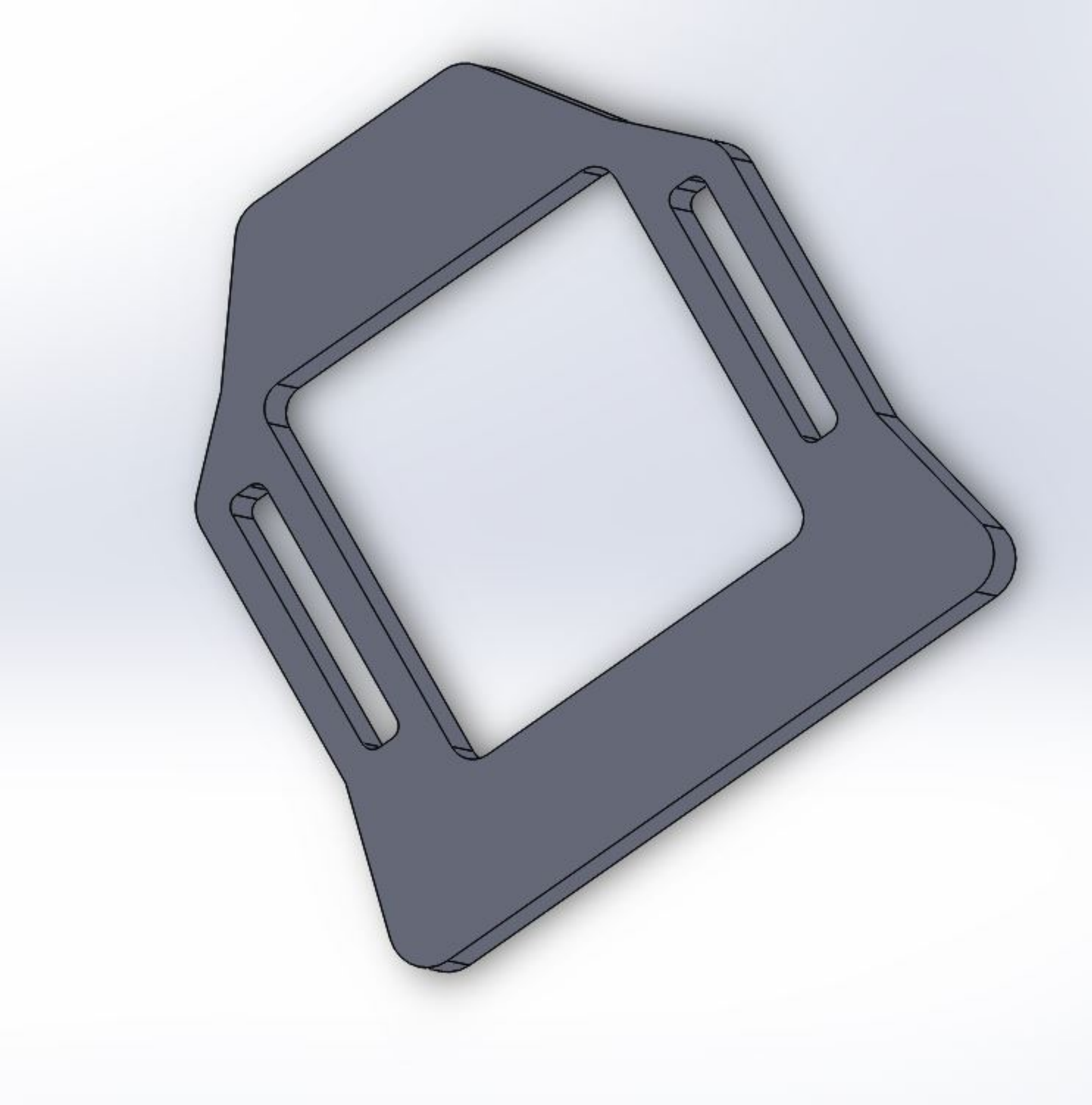


Figure B-2: Vicon marker plate design for foot IMU. Reflective markers were affixed to the top of the trapezoid and at the bottom left and right corners.

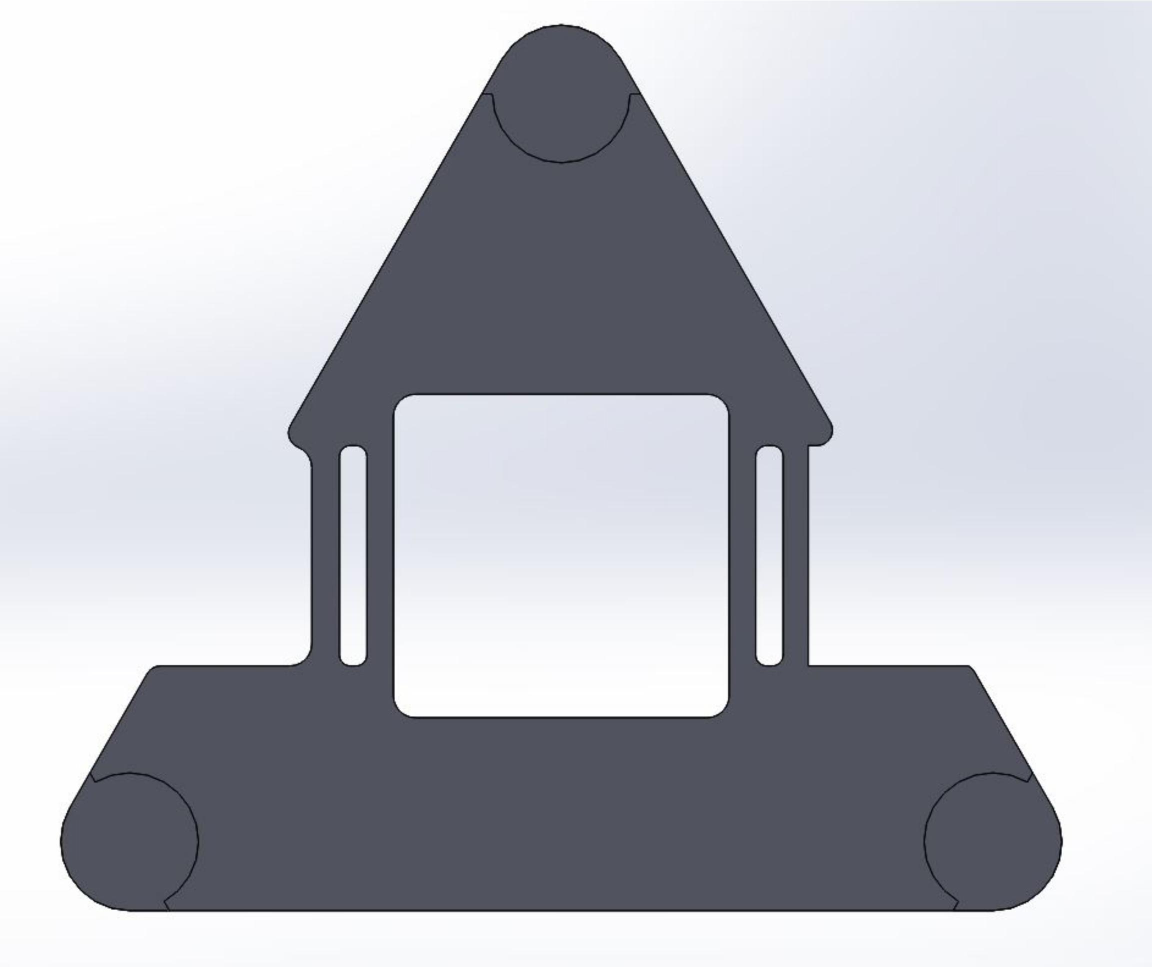
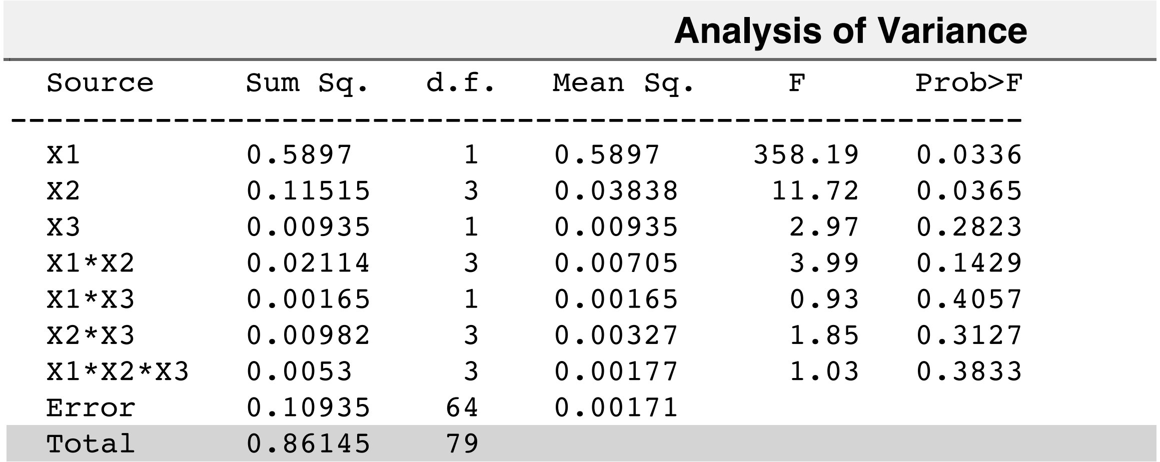


Figure B-3: Vicon marker plate design for sacrum IMU. Reflective markers were affixed at each corner of the triangle.

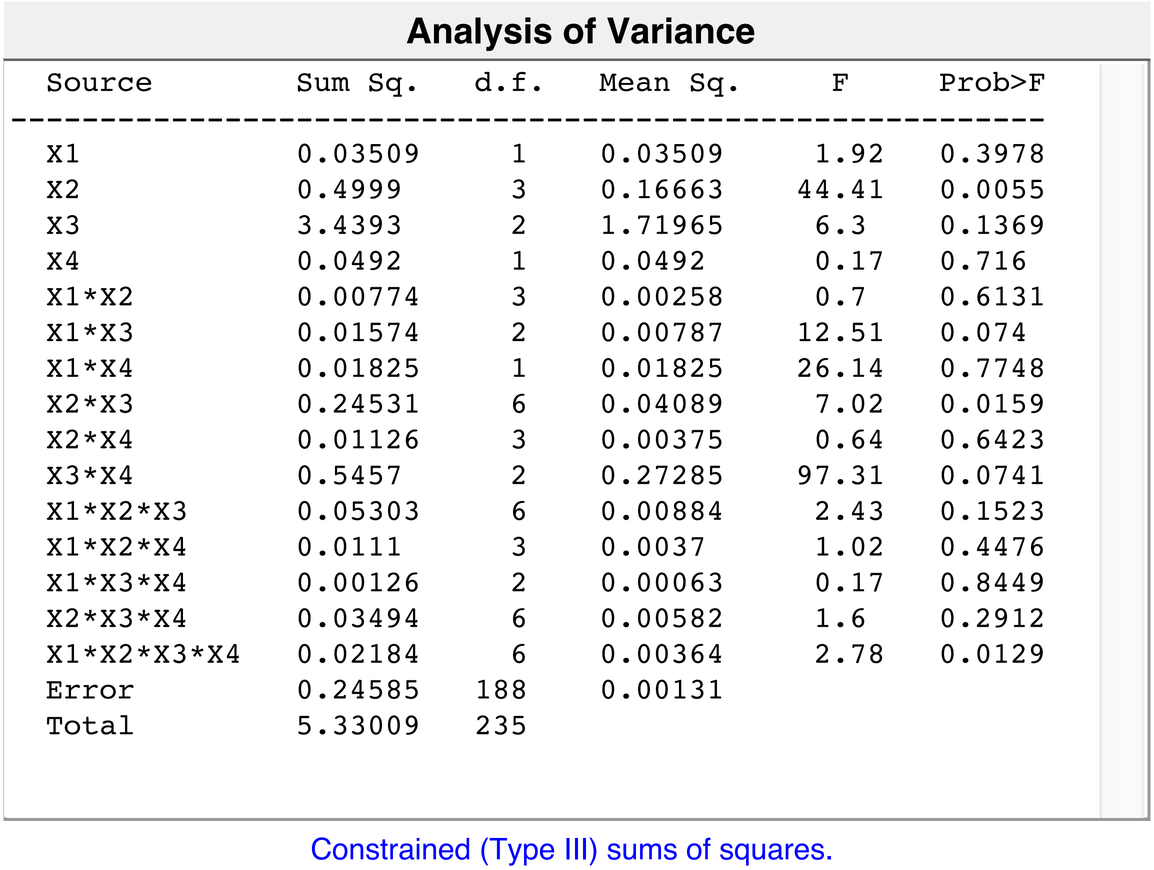
Appendix C

Pilot Study ANOVA Models



```
                                            Analysis of Variance
  Source       Sum Sq.   d.f.   Mean Sq.      F       Prob>F
-----------------------------------------------------------
  X1          0.5897       1    0.5897      358.19    0.0336
  X2          0.11515      3    0.03838      11.72    0.0365
  X3          0.00935      1    0.00935       2.97    0.2823
  X1*X2       0.02114      3    0.00705       3.99    0.1429
  X1*X3       0.00165      1    0.00165       0.93    0.4057
  X2*X3       0.00982      3    0.00327       1.85    0.3127
  X1*X2*X3    0.0053       3    0.00177       1.03    0.3833
  Error       0.10935     64    0.00171
  Total       0.86145     79
```

Figure C-1: ANOVA table of completion time metric. X1 refers to the factor of trial type, X2 refers to cone, and X3 refers to subject.

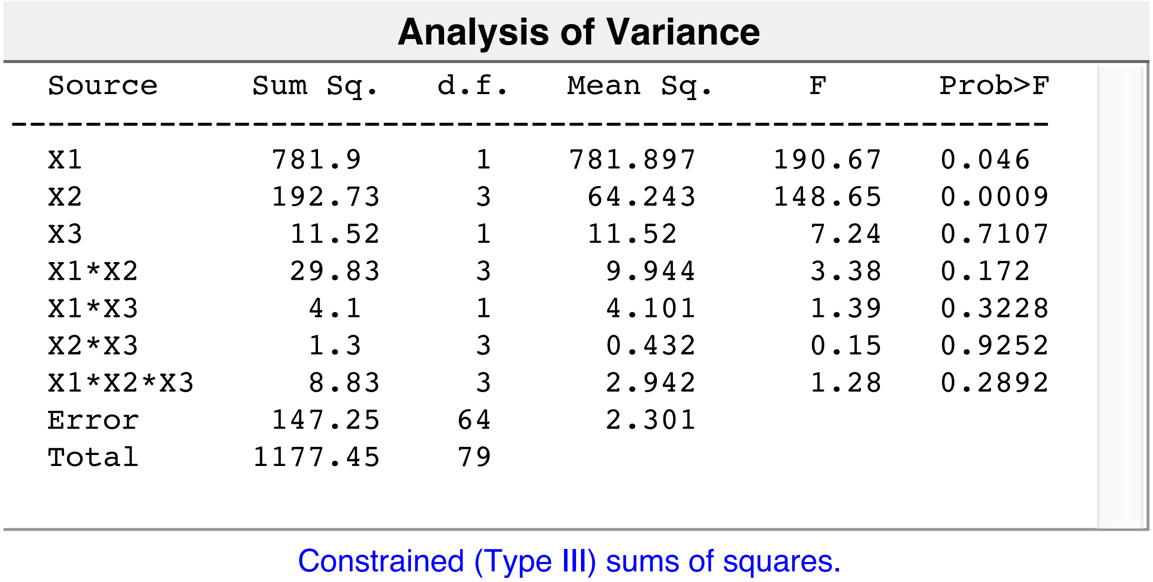


Analysis of Variance

```
  Source             Sum Sq.    d.f.    Mean Sq.      F      Prob>F
---------------------------------------------------------------------
  X1                 0.03509      1     0.03509      1.92    0.3978
  X2                 0.4999       3     0.16663     44.41    0.0055
  X3                 3.4393       2     1.71965      6.3     0.1369
  X4                 0.0492       1     0.0492       0.17    0.716
  X1*X2              0.00774      3     0.00258      0.7     0.6131
  X1*X3              0.01574      2     0.00787     12.51    0.074
  X1*X4              0.01825      1     0.01825     26.14    0.7748
  X2*X3              0.24531      6     0.04089      7.02    0.0159
  X2*X4              0.01126      3     0.00375      0.64    0.6423
  X3*X4              0.5457       2     0.27285     97.31    0.0741
  X1*X2*X3           0.05303      6     0.00884      2.43    0.1523
  X1*X2*X4           0.0111       3     0.0037       1.02    0.4476
  X1*X3*X4           0.00126      2     0.00063      0.17    0.8449
  X2*X3*X4           0.03494      6     0.00582      1.6     0.2912
  X1*X2*X3*X4        0.02184      6     0.00364      2.78    0.0129
  Error              0.24585    188     0.00131
  Total              5.33009    235
```

Constrained (Type III) sums of squares.

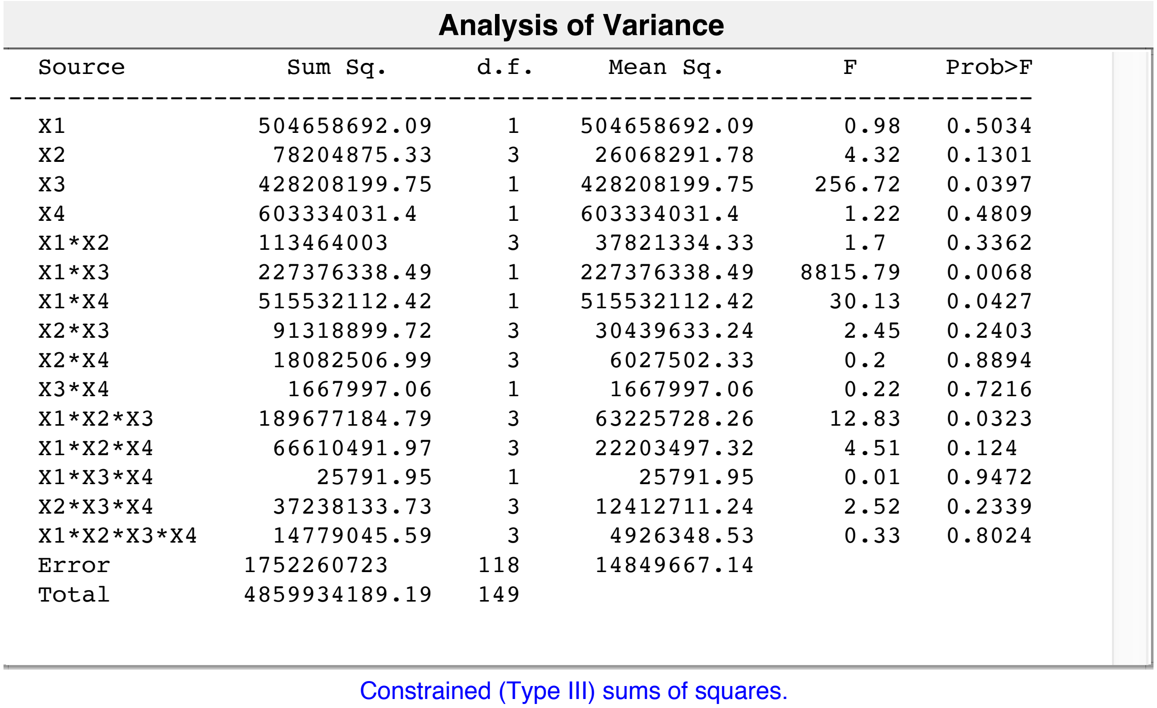
Figure C-2: ANOVA table of analysis for path length comparisons using Vicon-based estimates. X1 refers to the factor of trial type, X2 refers to cone, X3 refers to body location, and X4 refers to subject. Four samples were excluded from analysis due to dropout of the Vicon markers on the left heel beyond the 0.85m boundary mark.



```
                     Analysis of Variance
Source      Sum Sq.   d.f.   Mean Sq.       F      Prob>F
--------------------------------------------------------
X1           781.9      1    781.897    190.67    0.046
X2           192.73     3     64.243    148.65    0.0009
X3            11.52     1     11.52       7.24    0.7107
X1*X2         29.83     3      9.944      3.38    0.172
X1*X3          4.1      1      4.101      1.39    0.3228
X2*X3          1.3      3      0.432      0.15    0.9252
X1*X2*X3       8.83     3      2.942      1.28    0.2892
Error        147.25    64      2.301
Total       1177.45    79

           Constrained (Type III) sums of squares.
```

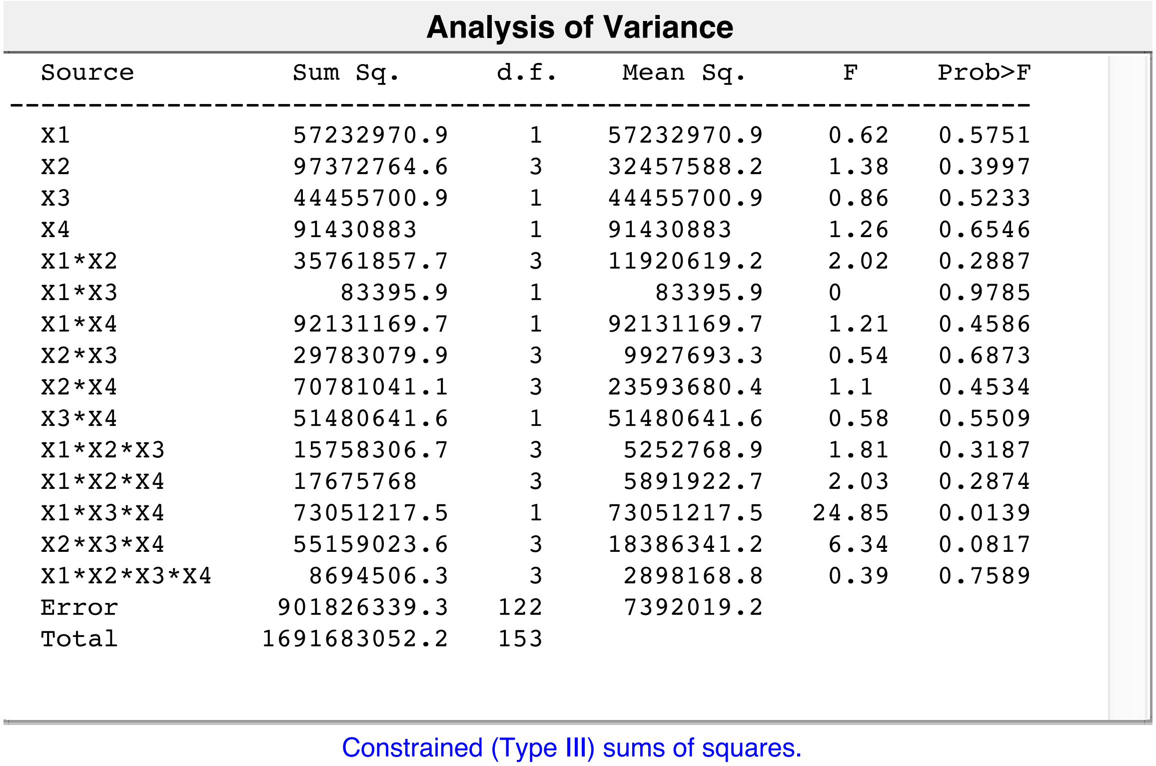
Figure C-3: ANOVA table of analysis for sacrum integrated comparisons using Vicon-based estimates. X1 refers to the factor of trial type, X2 refers to cone, and X3 refers to subject.



```
                           Analysis of Variance
Source              Sum Sq.       d.f.    Mean Sq.          F       Prob>F
--------------------------------------------------------------------------
X1              504658692.09       1    504658692.09       0.98    0.5034
X2               78204875.33       3     26068291.78       4.32    0.1301
X3              428208199.75       1    428208199.75     256.72    0.0397
X4              603334031.4        1    603334031.4        1.22    0.4809
X1*X2           113464003          3     37821334.33       1.7     0.3362
X1*X3           227376338.49       1    227376338.49    8815.79    0.0068
X1*X4           515532112.42       1    515532112.42      30.13    0.0427
X2*X3            91318899.72       3     30439633.24       2.45    0.2403
X2*X4            18082506.99       3      6027502.33       0.2     0.8894
X3*X4             1667997.06       1      1667997.06       0.22    0.7216
X1*X2*X3        189677184.79       3     63225728.26      12.83    0.0323
X1*X2*X4         66610491.97       3     22203497.32       4.51    0.124
X1*X3*X4            25791.95       1        25791.95       0.01    0.9472
X2*X3*X4         37238133.73       3     12412711.24       2.52    0.2339
X1*X2*X3*X4      14779045.59       3      4926348.53       0.33    0.8024
Error          1752260723        118     14849667.14
Total          4859934189.19     149

                 Constrained (Type III) sums of squares.
```

Figure C-4: ANOVA table of analysis for $D_{unsmooth}$. X1 refers to the factor of trial type, X2 refers to cone, X3 refers to body location, and X4 refers to subject. Four samples were excluded from analysis due to dropout of the Vicon markers on the left heel beyond the 0.85m boundary mark. Six samples were excluded from analysis due to issues with calculating IMU-based integrated curvature.

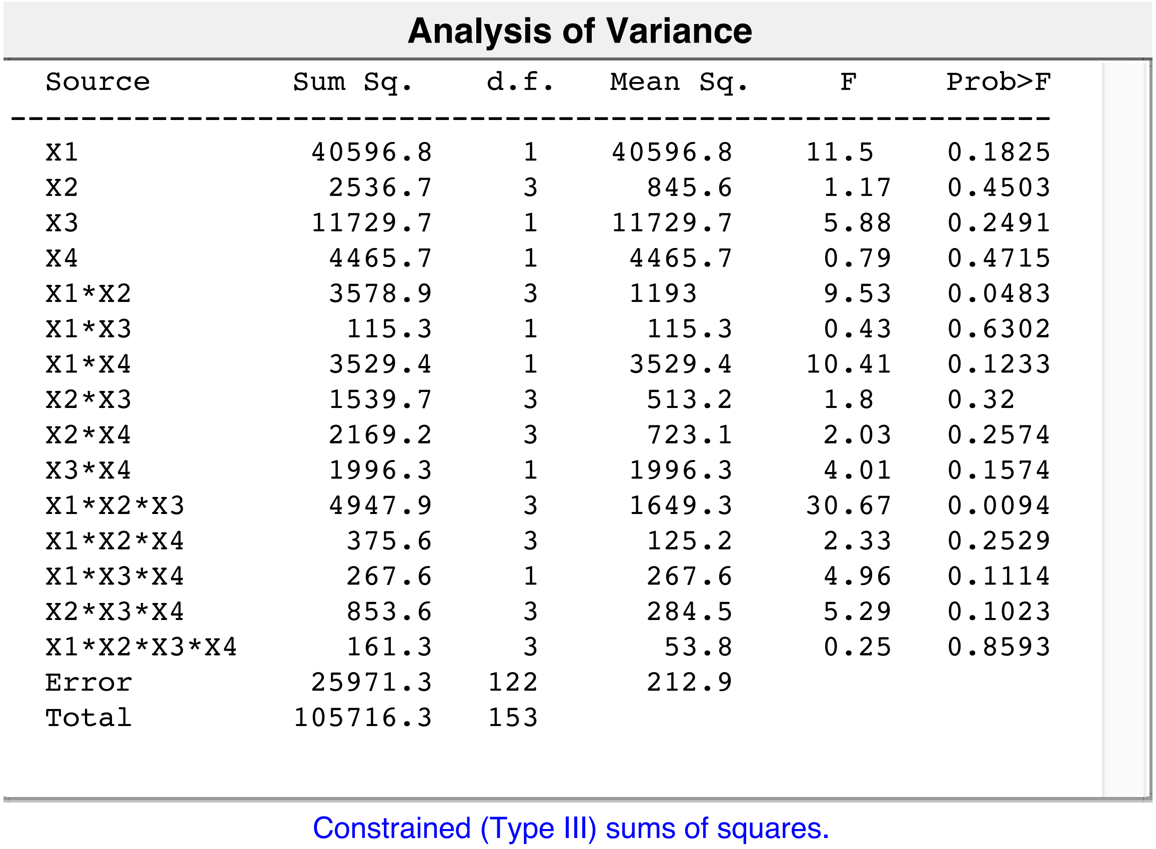


Analysis of Variance

```
  Source            Sum Sq.     d.f.    Mean Sq.      F     Prob>F
-----------------------------------------------------------------
  X1              57232970.9     1    57232970.9    0.62   0.5751
  X2              97372764.6     3    32457588.2    1.38   0.3997
  X3              44455700.9     1    44455700.9    0.86   0.5233
  X4              91430883       1    91430883      1.26   0.6546
  X1*X2           35761857.7     3    11920619.2    2.02   0.2887
  X1*X3              83395.9     1       83395.9    0      0.9785
  X1*X4           92131169.7     1    92131169.7    1.21   0.4586
  X2*X3           29783079.9     3     9927693.3    0.54   0.6873
  X2*X4           70781041.1     3    23593680.4    1.1    0.4534
  X3*X4           51480641.6     1    51480641.6    0.58   0.5509
  X1*X2*X3        15758306.7     3     5252768.9    1.81   0.3187
  X1*X2*X4        17675768       3     5891922.7    2.03   0.2874
  X1*X3*X4        73051217.5     1    73051217.5   24.85   0.0139
  X2*X3*X4        55159023.6     3    18386341.2    6.34   0.0817
  X1*X2*X3*X4      8694506.3     3     2898168.8    0.39   0.7589
  Error          901826339.3   122     7392019.2
  Total         1691683052.2   153
```

Constrained (Type III) sums of squares.

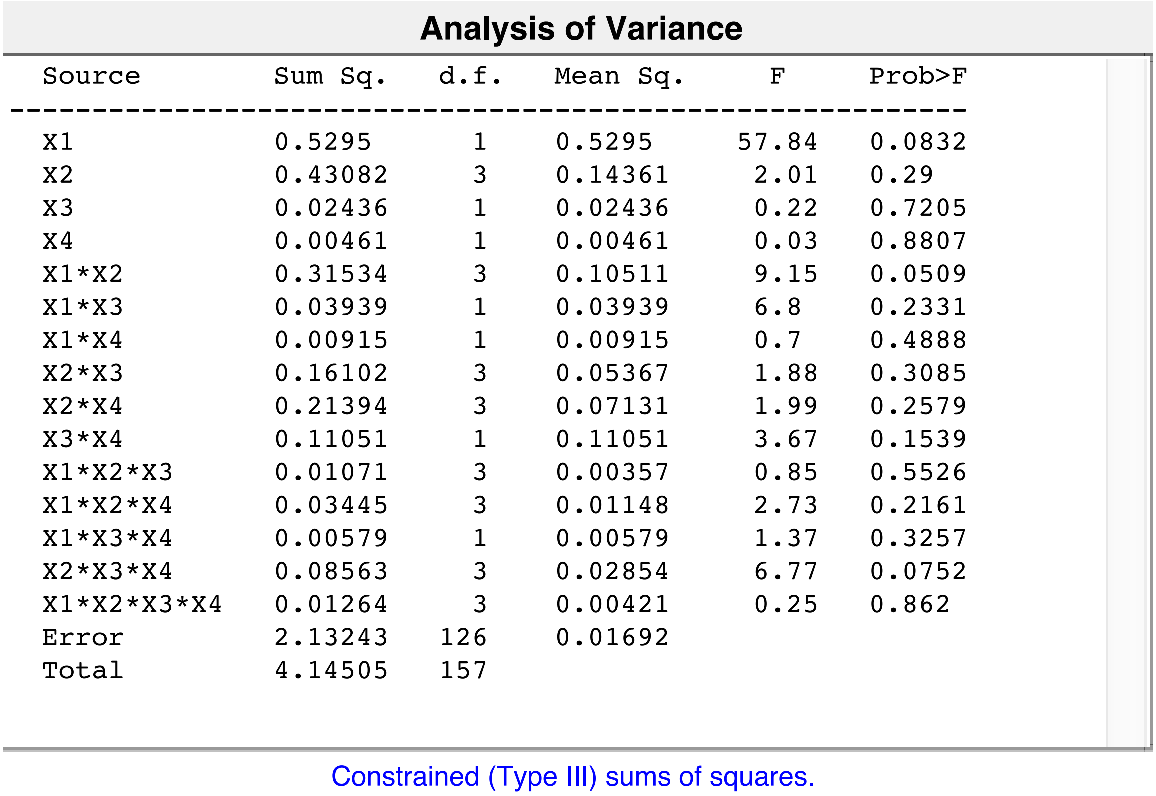
Figure C-5: ANOVA table of analysis for D_{smooth}. X1 refers to the factor of trial type, X2 refers to cone, X3 refers to body location, and X4 refers to subject. Four samples were excluded from analysis due to dropout of the Vicon markers on the left heel beyond the 0.85m boundary mark. Two samples were excluded from analysis due to issues with calculating IMU-based integrated curvature.



```
                              Analysis of Variance
  Source           Sum Sq.     d.f.   Mean Sq.      F       Prob>F
-------------------------------------------------------------------
  X1               40596.8       1    40596.8     11.5      0.1825
  X2                2536.7       3      845.6      1.17     0.4503
  X3               11729.7       1    11729.7      5.88     0.2491
  X4                4465.7       1     4465.7      0.79     0.4715
  X1*X2             3578.9       3     1193        9.53     0.0483
  X1*X3              115.3       1      115.3      0.43     0.6302
  X1*X4             3529.4       1     3529.4     10.41     0.1233
  X2*X3             1539.7       3      513.2      1.8      0.32
  X2*X4             2169.2       3      723.1      2.03     0.2574
  X3*X4             1996.3       1     1996.3      4.01     0.1574
  X1*X2*X3          4947.9       3     1649.3     30.67     0.0094
  X1*X2*X4           375.6       3      125.2      2.33     0.2529
  X1*X3*X4           267.6       1      267.6      4.96     0.1114
  X2*X3*X4           853.6       3      284.5      5.29     0.1023
  X1*X2*X3*X4        161.3       3       53.8      0.25     0.8593
  Error            25971.3     122      212.9
  Total           105716.3     153

                    Constrained (Type III) sums of squares.
```

Figure C-6: ANOVA table of integrated curvature analysis based on unsmoothed IMU estimates. X1 refers to the factor of trial type, X2 refers to cone, X3 refers to body location, and X4 refers to subject. Six samples were excluded from analysis due to issues with calculating IMU-based integrated curvature.



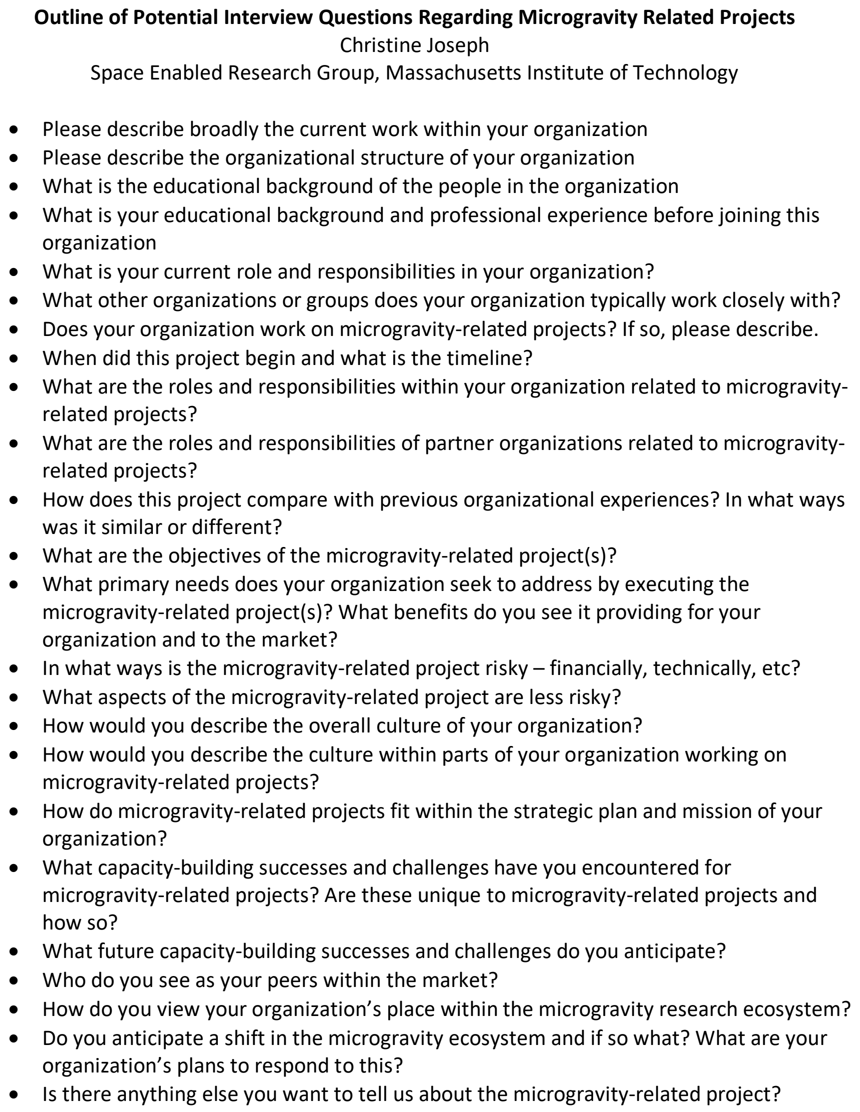
```
                              Analysis of Variance
  Source          Sum Sq.   d.f.   Mean Sq.      F      Prob>F
---------------------------------------------------------------
  X1              0.5295       1   0.5295     57.84    0.0832
  X2              0.43082      3   0.14361     2.01    0.29
  X3              0.02436      1   0.02436     0.22    0.7205
  X4              0.00461      1   0.00461     0.03    0.8807
  X1*X2           0.31534      3   0.10511     9.15    0.0509
  X1*X3           0.03939      1   0.03939     6.8     0.2331
  X1*X4           0.00915      1   0.00915     0.7     0.4888
  X2*X3           0.16102      3   0.05367     1.88    0.3085
  X2*X4           0.21394      3   0.07131     1.99    0.2579
  X3*X4           0.11051      1   0.11051     3.67    0.1539
  X1*X2*X3        0.01071      3   0.00357     0.85    0.5526
  X1*X2*X4        0.03445      3   0.01148     2.73    0.2161
  X1*X3*X4        0.00579      1   0.00579     1.37    0.3257
  X2*X3*X4        0.08563      3   0.02854     6.77    0.0752
  X1*X2*X3*X4     0.01264      3   0.00421     0.25    0.862
  Error           2.13243    126   0.01692
  Total           4.14505    157

                    Constrained (Type III) sums of squares.
```

Figure C-7: ANOVA table of integrated curvature analysis based on smoothed IMU estimates. X1 refers to the factor of trial type, X2 refers to cone, X3 refers to body location, and X4 refers to subject. Two samples were excluded from analysis due to issues with calculating IMU-based integrated curvature.

Appendix D

Sample Field Interview Questions



Outline of Potential Interview Questions Regarding Microgravity Related Projects
Christine Joseph
Space Enabled Research Group, Massachusetts Institute of Technology

- Please describe broadly the current work within your organization
- Please describe the organizational structure of your organization
- What is the educational background of the people in the organization
- What is your educational background and professional experience before joining this organization
- What is your current role and responsibilities in your organization?
- What other organizations or groups does your organization typically work closely with?
- Does your organization work on microgravity-related projects? If so, please describe.
- When did this project begin and what is the timeline?
- What are the roles and responsibilities within your organization related to microgravity-related projects?
- What are the roles and responsibilities of partner organizations related to microgravity-related projects?
- How does this project compare with previous organizational experiences? In what ways was it similar or different?
- What are the objectives of the microgravity-related project(s)?
- What primary needs does your organization seek to address by executing the microgravity-related project(s)? What benefits do you see it providing for your organization and to the market?
- In what ways is the microgravity-related project risky – financially, technically, etc?
- What aspects of the microgravity-related project are less risky?
- How would you describe the overall culture of your organization?
- How would you describe the culture within parts of your organization working on microgravity-related projects?
- How do microgravity-related projects fit within the strategic plan and mission of your organization?
- What capacity-building successes and challenges have you encountered for microgravity-related projects? Are these unique to microgravity-related projects and how so?
- What future capacity-building successes and challenges do you anticipate?
- Who do you see as your peers within the market?
- How do you view your organization's place within the microgravity research ecosystem?
- Do you anticipate a shift in the microgravity ecosystem and if so what? What are your organization's plans to respond to this?
- Is there anything else you want to tell us about the microgravity-related project?

Figure D-1: Copy of the sample field interview questions distributed to interviewees. Some emergent or topic specific questions were additionally asked based on an interviewees particular experience or the course of the conversation.

Appendix E

Socio-technical Milestones in ISS Development

The ISS is the single largest and most expensive human construction project. An international endeavor, the ISS has been continuously occupied by humans since 2000. International partners include the USA, Russia, Canada, Japan, and the European Space Agency (ESA) member countries and as of June 2018, individuals from 18 different countries have visited the station [143]. Although main construction of the ISS ran from 1998 to 2011, the origins of its development can be traced to the founding charter of NASA.

The National Aeronautics and Space Act of 1958, which formally established NASA, stated that one of the objectives of the newly created agency was "Cooperation by the United States with other nations and groups of nations in work done pursuant to this Act and in the peaceful application of the results, thereof;" (Sec 102 (c)(7)) [144]. In the post-Apollo era, such cooperation engagements evolved from "data exchange, working together on scientific projects and providing launch services for the scientific satellites of other countries" to directly involving foreign partners in providing critical human spaceflight hardware [145]. In late 1969, NASA asked Canada, Europe, and Japan to consider options of participating in post-Apollo human spaceflight. Ultimately, Canada agreed to develop and provide the Remote Manipulator System (Canadarm 1) for the space shuttle and Europe agreed to the option of providing a Research and Applications Module (later called SpaceLab) for the shuttle. Setbacks in projected usage of the shuttle and development delays meant that ESA – established in 1975 – never recouped the development costs of SpaceLab and resulted in some tensions between NASA and ESA [145]. Nevertheless, these post-Apollo cooperation agreements proved that Canada and Europe could manage and build human spaceflight-rated hardware projects. Beyond the experience gained in systems engineering, management and technical knowledge, both these regions and the U.S. gained more confidence in their respective spaceflight capabilities. Such hardware successes contributed to Canada and Europe's ability to approach later cooperative discussions on a more equitable footing.

In 1981, President Reagan nominated James Beggs as NASA administrator and Hans Mark as deputy administrator. At their confirmation hearing, Beggs and Mark announced intent for a permanent, human-tended space station as the next major and logical goal in space [145, 146]. Different NASA field centers had conducted studies on possible space station missions and configurations, but an official program had yet to receive approval. In November 1981, a NASA-wide workshop was held on space station planning, in which international participation and cooperation figured significantly in the discussions [145]. A Space Station Task Force, headed by John Hodge, was formally created in May 1982 and possible international partners were encouraged to run their own requirements studies. In August 1982, NASA awarded contracts to U.S. aerospace firms to conduct independent and parallel requirements analysis studies for a space station. The firms received some pushback from the Department of Defense, however, when they began exploring options for cooperating with foreign firms due to arms control and technology transfer issues. Following such pushback, NASA international affairs officials (Kenneth Pederson and Margaret Finarelli) continued to move forward with the task force, but tactfully chose not to emphasize international involvement in external advocacy discussions in order to avoid resistance from other agencies [145]. In 1982, NASA unsuccessfully sought President Reagan's approval to embark on a space station project. Reagan's July 1982 space policy address transferred space policy leadership from the Office of Science and

Technology Policy to the National Security Council (NSC). Fortunately for space station proponents the space policy representative in the NSC, Air Force Colonel Gil Rye, had participated in the NASA space station workshop in 1981 and believed that building a space station was critical for U.S. national security in the Cold War era [145, 147].

From 1982 to 1984, NASA officials again sought presidential endorsement of a space station, through prescribed working groups and direct discussions with the president and his advisors that were facilitated by Rye [145, 147, 148]. Eventually officials were successful in gaining Reagan's approval. In his 1984 State of the Union address, Reagan not only announced the decision to build the space station, but also invited international participants. Discussions by top national security, NASA, and State department officials right before the address facilitated the inclusion of international cooperation in the speech and bypassed the bureaucracy of policy papers, assessments, and inter-agency meetings that would typically accompany such an announcement [145]. By incorporating the international element into Reagan's speech, officials helped insulate the project from future critics as an attack on the project would come to be seen as an attack on American international prestige [148].

Even after gaining a presidential endorsement, the space station project faced an uphill battle of congressional appropriations, competing field center plans, and difficulty in defining the purpose of the project itself. A development budget for the station was approved piecemeal each year in the late 1980s and estimated total costs of the project began to rise over $10 billion. Winter of 1985 began with NASA leadership changes and sadly ended with the Challenger explosion. The subsequent findings of the Rogers Commission and Augustine Commission, along with Hubble difficulties highlighted management issues within NASA and drove a desire to scale back or even cancel the space station program within Congress [149, 150]. In 1991 and 1993, the space station project, now called "Freedom", narrowly won congressional votes for continued funding. Although individual representatives may have opposed the project, lobbying from aerospace firms, interests of constituent states with NASA centers, and a stake in international prestige helped save the project. In the late

1980s, MOUs had been signed with Canada, Europe and Japan for engagement in the project and by the early 1990s, these partner countries had already spent $1.6 billion between them on Freedom. Canceling the project would not only be viewed as an affront to these international partnerships but also a waste of NASA dollars that had already been spent [148].

In the midst of these troubles for the space station in the U.S., political winds were shifting on the other side of the globe. The year 1991 marked the dissolution of the Soviet Union and the beginning of financial, logistical and technical troubles for the newly formed Russian Space Agency (RSA). The RSA was dealing with a sudden loss of funding, revolts at their remote launch site in Kazakhstan, old Mir hardware, and conflicts over the construction of Soyuz hardware. In June 1992, NASA chief Dan Goldin and RSA head Yuri Koptev met and discussed possible solutions for each other's problems - NASA needed increased momentum and funding to keep the space station project going and Russia still maintained most of its spaceflight supply capacity [148]. In 1993, station redesign recommendations by the Vest Committee contained proposals to include Russia in the planning and building of the station. In September that year, Vice President Al Gore, Russian Prime Minister Victor Chernomyrdin, and the respective space chiefs signed a deal for Russia to be involved in the space station, renaming the project International Space Station Alpha [151–153]. Building off of previous collaboration from the *Apollo-Soyuz Test Project*, Phase One of the program involved *Shuttle-Mir* collaborations that helped define and establish the technical logistics of the two programs working together [154]. The deal not only helped keep the space station program alive, but was beneficial for foreign policy interests to stabilize relations with Russia as a whole.

In 1995, Boeing signed a $5.6 billion deal for the prime ISS contract and Johnson Space Center (JSC) was designated as leader of the project. Following NASA successes with fixing the Hubble Space Telescope and public support after the release of the feature film Apollo 13, NASA chief Goldin sought and won a multi-year authorization of the space station program [148]. Doing so assured long-term funding for the proposed station construction years and satisfied international pressure to continue the project. Following approval of the multi-year authorization in the U.S., ESA also voted to continue support of the ISS. In January of 1998, the ISS Intergovernmental Agreement (IGA) was signed between the U.S., Canada, member states of ESA, the government of Japan, and the Russian Federation on the cooperation of the civil International Space Station [65].

In November 1998, the Zarya module was launched by Russia as the first segment of the ISS [155]. Financed by the U.S. and built by Russia, the control module had been plagued by delays. Two weeks later, the U.S. built Unity node was launched from a space shuttle (STS-88) and docked with Zarya. Following another two-year delay, the Russian developed Zvezda Service Module was launched and docked with Zarya-Unity. The service module provided a central hub to the ISS with engines, docking ports, life support, and living quarters [155]. Its addition enabled the station to be permanently inhabited by a crew. In October 2000, Expedition One crew entered the ISS, marking the beginning of continued human habitation in space.

The following years saw continued crew residencies and module additions of laboratories, nodes, Canadarm 2, trusses, and solar arrays. However, the Columbia shuttle disaster resulted in a two-year stand down of ISS construction and downsizing of the final station plans. After shuttle launches restarted in 2005, additional modules from the partner countries and support structures were added until the main ISS construction was completed in 2011 [69, 155, 156]. The ISS program has been an enterprise over 30 years in the making. Bringing the program to fruition depended not only on the technical expertise and capability to design and build spaceflight hardware, but also the leadership of driven individuals, international commitment, and the nature of funding governmental space programs. The leadership and focus of individuals like Beggs, Mark, Hodge, Pedersen, Finarelli, and Rye secured presidential endorsement at the onset of the program while also tactfully addressing national security concerns. The efforts of subsequent NASA leaders, particularly Dan Goldin, played a significant role in maintaining funding for the project as it advanced from a development project to NASA's next major project in human spaceflight. The inclusion of international cooperation at the very beginning of space station planning enabled the program to utilize foreign funding and capabilities in development and also provide a layer of programmatic protection in the form of preserving America's reputation at the international stage. By taking advantage of early endorsement from top policy officials and fostering relationships biased towards continued cooperation among technical experts across borders, the ISS program leveraged international engagement for its continued development [145]. Although the funding mechanisms within NASA and among ESA member states often put the ISS program at the peril of Congress, such mechanisms paradoxically also ensured the space station's continued development, lest the economic throughput of certain states and the international standing of America to lead in human spaceflight be put at stake. These socio-technical influences drove the completion of the International Space Station and continue to influence the ecosystem in which the ISS operates as the major microgravity research platform.

Appendix F

Full Stakeholder Analysis

Table F.1: Full stakeholder analysis table. For each stakeholder categorization, a summary of their objectives, needs, and functions are detailed.

	Objective	Needs	Functions
ISS public space agencies	Execute agency missions as defined by domestic governments. Abide by terms of IGA and MOUs establishing ISS project. Support utilization of ISS for national scientific, technical, and economic development	Continuous public and political support and funding. A competent workforce (STEM and non-STEM) for continued development of projects. Clear priorities	Maintain operations of ISS through interagency mission control coordination; crew support; communications, data, and power handling; and crew/cargo transportation. Facilitate utilization by purpose-aligned domestic entities.

Table F.1 continued from previous page

	Objective	Needs	Functions
Parabolic flight operators	Provide a safe, high quality microgravity experience for governments and customers (entertainment, research, and education)	Enough customers to maintain business case or maintain regular utilization. Technically competent workforce to operate aircraft and maintain safe standards for passengers and experiments. Domestic regulatory support for unique flight route profile.	Operate flights for governmental and private customers. Provide technical support for researchers to ensure flight safety, customer satisfaction, hardware compatibility, and satisfaction of research goals. Facilitate opportunities for education flights and ground experiences that are free, public-sponsored, or private sponsored. Broker and participate in public interface activities.

Table F.1 continued from previous page

	Objective	Needs	Functions
Suborbital flight operators	Provide a safe, high quality microgravity experience for governments and customers (entertainment, research, and education)	Private funding and enough customers to maintain business case. Technically competent workforce to develop and operate craft and maintain safe standards for passengers and experiments. Domestic regulatory support for launches.	Operate flights for governmental and private customers. Provide technical support for researchers to ensure flight safety, customer satisfaction, hardware compatibility, and satisfaction of research goals. Facilitate opportunities for education flights and ground experiences that are free, public-sponsored, or private sponsored. Broker and participate in public interface activities.

Table F.1 continued from previous page

	Objective	Needs	Functions
Private ISS facility operators	Operate internal or external ISS research facility for own and customers' projects	Private funding and enough customers to maintain business case. Support (installation, crew experimenter/operator, comms/data/power handling, return stowage, publicity) from an ISS public agency. Governmental or private funding. Connections with potential customers.	Interface with public ISS space agency (either through a public interface or directly with space agency) to coordinate installation, rack space, comms/data/power handling, and upmass/downmass manifestation. Various levels of technical support and integration services. Some offer lower education based pricing. Depending on customer funding source and form of access, offer IP protections.

Table F.1 continued from previous page

	Objective	Needs	Functions
Commercial transport	Provide a safe, high quality flight for governments and customers (military, commercial, civil)	Private funding and enough customers to maintain business case. Technically competent workforce to develop and operate vehicles and maintain safe standards for payloads. Domestic regulatory support for launches.	Operate flights for governmental and private customers. Provide launch and payload safety specifications to customers and regulators to ensure flight safety, customer satisfaction, hardware compatibility, and satisfaction of customer goals. Broker and participate in public interface activities. Lobby for contracts and “friendly” and responsible regulations.
Public transport	Provide a safe, high quality flight for governments and customers (military, commercial, civil)	Public funding and enough utilization to maintain operations. Technically competent workforce to develop and operate vehicles and maintain safe standards for payloads. Public support from government.	Operate flights for governmental and private customers. Provide launch and payload safety specifications to customers and regulators to ensure flight safety, customer satisfaction, hardware compatibility, and satisfaction of customer goals. Broker and participate in public interface activities. Bid for contracts and lobby “friendly” and responsible regulations.

Table F.1 continued from previous page

	Objective	Needs	Functions
National public interfaces	Connect public with services offered by public agency and promote effective utilization of assets.	Public funding and enough end users to justify continued public funding. Public and private assets to offer as services. Clear priorities	Connect end-users with public, public-private, or completely private platforms. Put out a solicitation call for projects, broker with technical experts at the interface firm or platform firm, arrange up-mass/down mass allocations, and occasionally allocate some level of funding to users.
International public interfaces	Promote international cooperation around globe and in regional areas. Bridge the space divide between developing countries and spacefaring nations.	Support of member countries for funding and continued utilization by developing countries to demonstrate results. Support from space faring countries and private partners.	Connect end-users with public, public-private, or completely private platforms. Put out a solicitation call for projects, broker with technical experts at the interface firm or platform firm, arrange up-mass/down mass allocations, and occasionally allocate some level of funding to users.

Table F.1 continued from previous page

	Objective	Needs	Functions
Legislative body	Represent views of constituents in the making of public law and appropriation of public funding.	Public and political party support. Successful re-election campaigns.	Legislate public law and regulations. Authorize and appropriate public space funding. Influence other public policy makers.
Executive body	Execute and enforce public law. Operate public space agencies. Set domestic policy and strategy.	Public and political party support. Appropriated funding.	Operate public space agencies. Enforce regulations. Set forth domestic policy directives and strategies.
Regulatory body	Enforce public law and policy within mission of relevant regulatory agency.	Public funding. Policy directives from executive body. Clear laws authorizing purview of operations.	Regulate launch licenses, spectrum allocations, and export control. Set forth new regulations in line with public policies and changing operational environments.

Table F.1 continued from previous page

	Objective	Needs	Functions
All commercial end users	Make profits and maintain market competitiveness in alignment with mission of company.	Innovative products. Capital funding for research, development, and production. Competent STEM workforce. Shareholder support if publicly held.	Respond to funding solicitations and research opportunities that can give products a leading edge in markets. Work directly with a platform operator, public interface, or integration services to manifest project.
All public end users	Develop strategy and technology roadmaps to accomplish own and agency level science and technology goals. Propose, fund, and execute projects to achieve milestones in roadmaps.	Continuous public and political support and funding. A competent workforce (STEM and non-STEM) for continued development of projects. Clear priorities.	Develop roadmaps to achieve objectives. Execute projects to achieve roadmap milestones in-house or through commercial/academic solicitation calls. Manifest satisfactory and goal-aligned projects on a microgravity platform.

Table F.1 continued from previous page

	Objective	Needs	Functions
All integration services	Meet customer needs for payload integration and ensure safe flight.	Funding and enough customers to maintain business case. Technically competent workforce to develop and operate systems and maintain safe standards for payloads. Clear regulations and specifications on certifications. Communication with end users and platform suppliers.	Market services to end users, public interfaces, and private platform operators. Develop procedures for payload compatibility in terms of power, data, and communications handling. Ensure compliance with safety testing and relevant regulations. Manifest projects and arrange for return of results.
Public funding entities	Support public mission of organization by distributing public funds to worthy candidates.	Public funding and organizational support. Clear priorities and metrics to ensure continued support.	Solicit and distribute funding opportunities to relevant end users and public interfaces. Evaluate applications for merit and alignment with public goals.
Private funding entities	Seek out and invest in projects and firms that will supply a favorable return on investment.	Communications and networking with entrepreneurs. Clear regulatory environment to work in. Stable or growing marketplace.	Fund entrepreneurs whose projects and firms show potential for a favorable return on investment. Seek out other investors to join in portfolio. Publish reports and comply with regulations.

Table F.1 continued from previous page

	Objective	Needs	Functions
Non orbital platforms	Provide a safe, high quality microgravity experience for governments and customers (entertainment, research, and education) to raise technology readiness levels and test out subsystems.	Enough customers to maintain business case or maintain regular utilization. Technically competent workforce to operate craft and maintain safe standards for passengers and experiments. Domestic regulatory support for operations (flight and launches).	Operate flights for governmental and private customers. Provide technical support for researchers to ensure flight safety, customer satisfaction, hardware compatibility, and satisfaction of research goals. Facilitate opportunities for education flights and ground experiences that are free, public-sponsored, or private sponsored. Broker and participate in public interface activities. Stay up to date on new orbital standards for safety and certifications.
K through 12, undergraduate	Educate students in STEAM.	Public funding and support from school, students, and parents. Technical expertise. Continuous motivation.	Reach out to platform suppliers, higher level academic group, or public agencies if interested in a project. Participate in publicly and privately sponsored competitions.

Table F.1 continued from previous page

	Objective	Needs	Functions
Non space and early career	Pursue research projects that align with research interests and advance field.	Funding and support from university or sponsor. Technical expertise. Information about how microgravity environment can be leveraged for relevant field. Timely return of results for analysis and publication.	Seek out funding opportunities, information and technical expertise from a variety of sources. Execute projects and publish results.
Emerging space nations	Build capacity for STEM fields. Participate in space activity to support national priorities. Increase economic development.	Partnerships with other countries and private organizations. Seed funding or payload slot on a platform. Networking for technical expertise. Access to resources and workforce.	Respond to solicitations from public interfaces. Form national policies and dedicate funds in an organization or public agency towards accomplishing space activity projects. Seek out partnerships. Continue space participation beyond STEM education goals.

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