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Modular Multimodal CanBot Trajectory Tracking with Optical Motion Capture System

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***Abstract*—CanSats are earth bound analogues for orbital micro and picosatellites. These devices have become increasingly relevant as small-scale satellites, such as CubeSats, have grown in popularity and accessibility. With additional robotic frontiers for the exploration of space also becoming increasingly accessible, analogous systems for researching planetary surface rovers may also be potentially relevant. This research expands on the emerging field of "CanBots", which refers to this kind of earth-bound analogue for planetary surface exploring robots. The novel modular CanBot developed in this research represents a unique design framework whereby mobility aspects of the vehicle form discrete and interchangeable modules. Initial characterization of the locomotion capabilities of these modules were determined independently using an optical Motion Capture system. Then the modules were combined into a single multimodal system for additional mobility testing. Vehicle trajectories for an Aerial Quadrotor CanBot, Terrestrial Quadruped CanBot and the combined Multimodal CanBot have been compiled in this research. Initial results suggest that the Multimodal CanBot can successfully reproduce the locomotion techniques for the aerial and terrestrial modalities, but at the cost of lower overall movement efficiency in either modality.**

***Keywords*—CanBot, Multimodal Mobility, Motion Capture, MoCap, CanSat**

I. INTRODUCTION

Multimodal Mobility represents the capacity for a vehicle to engage multiple types of 'classical' locomotion techniques in a single unified device. Such classical techniques are typically well understood and widely utilized in various robotic systems. Examples could include multirotor aerial vehicles or terrestrial robots with articulated legs. The combination of these classical modalities into a single locomotion strategy represents a burgeoning field of robotic investigation [1]. In particular, the potential for such multimodal techniques to revolutionize the exploration of planetary surfaces is of particular interest.

As part of an ongoing study into advanced new techniques for robotic planetary surface exploration, the Modular Aerospace and Robotic Systems (MARS) laboratory at Kennesaw State University (KSU) continues to investigate novel CanSat and CanBot architectures [2]. Robotic CanSats provide a means for simulating orbital satellites with earth-bound robotic systems. Similarly, CanBots represent simulated surface exploration rovers, and offer a new extension to the existing fields of CanSats. The following document outlines initial mobility testing for a prototype multimodal CanBot developed at MARS Lab that represents a novel expansion on classical robotic mobility techniques. The testing regiment detailed herein focuses on the use of an optical Motion Capture (MoCap) system to record the movement of various CanBot robots. Existing literature was consulted to examine how MoCap systems have previously been employed to characterize the locomotion of unique robots. Relevant examples of such research have been included below.

A. Previous uses of Optical Motion Capture Systems

In optical-passive Motion Capture the position of reflective markers can be determined by the observation of those markers with multiple optical cameras arranged in a known configuration [3]. This technique has been utilized widely to test engineering models of future planetary surface rovers. Nasa's Jet Propulsion Laboratory (JPL) utilized optical-passive Motion Capture technologies to determine the wheel slippage for initial models of the Mars Science Laboratory (MSL). In figure 2, the MSL test analogue known as "scarecrow" is shown during field tests in the Mojave Desert. Both the motion tracking cameras and reflective markers are clearly visible. [4] More recently, testing of the proposed VIPER lunar rover has also employed similar technologies such as the "OptiTrack motion tracking camera system" [5], or "ArUco" markers for determining locomotion characteristics [6].

Fig. 1 Multimodal CanBot consisting of Aerial Quadrotor (top) and Terrestrial Quadruped (bottom) mobility modules.

Similar motion capturing techniques have also been employed for characterizing the motion of robots with multimodal capabilities. Researchers working on the Dynamic Underactuated Flying-Walking Robot, also known as “DUCK”, where able to compare theoretic walking gait to experimentally observed walking gait through a Motion Capture system [7]. As MoCap technologies are therefore relevant for characterizing the locomotion of multimodal robots and planetary surface rovers, this technique was further employed in this study. The following section outlines the methodologies developed for this research.

The following details the methods employed to test the CanBots while section III of this paper includes relevant results and assessment of the collected data. The final section of this paper includes the conclusion and potential future directions of this work.

II. METHODS

For the purposes of this study, a modular multimodal robot was constructed from an existing aerial quadrotor and a terrestrial quadruped mobility module. These modules were previously developed for a larger ecosystem of robotic vehicles called CanBots that are intended to simulate planetary surface exploring robots. In figure 1 the multimodal CanBot can be seen as an amalgamation of the Quadruped Module on the bottom of the CanBot, and the Quadrotor Module on the top of the robot. Adapting the classifications of multimodal robots developed by Kalantari Et al., the multimodal CanBot developed for this work could be considered a form of “Active Legged UAV” [8]. While other quadrupedal multimodal robots have been proposed and tested, [9], [10], [11], the CanBot paradigm developed herein presents a uniquely low cost and modularized methodology for developing multimodal robotic systems.

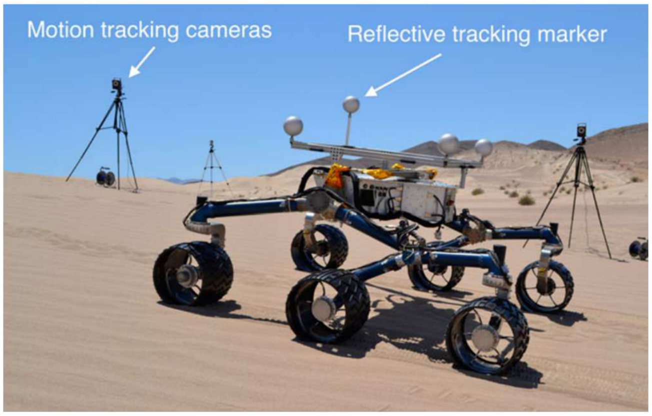
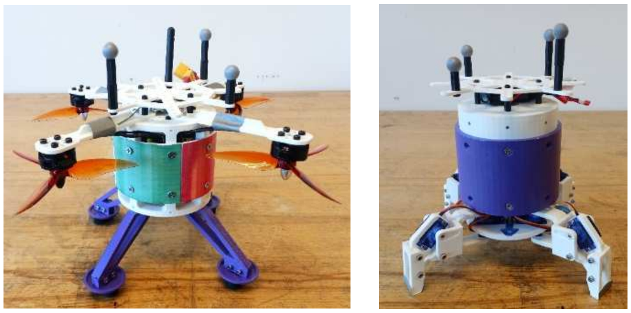


Fig. 2. MoCap setup for Nasa’s “scarecrow” rover [4].

To determine potential benefits and drawbacks of this new multimodal CanBot configuration, localization and tracking of the vehicle was required. A Motion Capture (MoCap) system consisting of eight OptiTrack Flex 3 cameras was employed in this study. The eight MoCap Cameras were mounted on the ceiling of the capture space. The overall capture space formed a square prism measuring approximately four meters wide by four meters long by three meters tall. At each of the top corners of this prism was mounted a MoCap camera, with additional cameras mounted on the edge of the prisms equidistant between the top corners. All cameras were angled downward and pointed generally toward the center of the floor at the base of capture space. Initial analysis of this configuration of cameras determined that the best capture results were obtained when testing was done in the two-meter square area at the center of the space. Subsequently, data analysis for this research has been focused primarily on results from this central area of the capture space.

The CanBots were equipped with custom 3D-printed MoCap marker arrays. These arrays consisted of 3D-printed plates that had regularly spaced holes. Nylon standoffs could be attached to these holes, and then the markers could be attached to the ends of the standoffs. By varying the height and location of the markers, unique arrangements of marker arrays could be generated. These marker arrays were further configured in the MoCap software, Motive, as rigid bodies and the centroids of the arrays were tracked to determine the movement characteristics of the CanBots.



(a) (b)

Fig. 3. Aerial Quadrotor CanBot (a) and Terrestrial Quadruped CanBot (b) both with MoCap Arrays.

In addition to the multimodal CanBot, data was also collected and analyzed for a monomodal CanBot consisting of only the aerial Quadrotor Module and another monomodal CanBot consisting of only the terrestrial Quadruped Module. These vehicles were intended to represent the “classical” mobility techniques that were combined into the final multimodal system. By first characterizing the locomotion of these vehicles as independent systems, further insight into the new multimodal technique could potentially be discerned. Notably, one of the novelties of the multimodal CanBot described previously was the capacity to be constructed rapidly from the same modularized components that were also utilized to create the aerial quadrotor CanBot and terrestrial quadruped CanBot. Transforming the multimodal CanBot into the two separate aerial and terrestrial CanBots could be completed in approximately three and a half minutes.

Data was collected at a rate of 100 Hz using Motive, and each capture session could be exported as a Comma Separated Value (CSV) document. In turn, this document was analyzed with MATLAB to generate the plots in the following section of this document. Additionally, a regular video camera was also erected at the top center of the capture space to view the movement of the CanBots from a planar “overhead” perspective. Video from this camera as well as screen capture of the Motive software was recorded and utilized to identify the appropriate section of the raw data to present in the following data analysis.

Four experimental setups were tested in this study, in each case consisting of the CanBots being manually driven in a straight trajectory. In the first setup, the multimodal CanBot was tested in a terrestrial walking locomotion strategy using the quadruped module. In the second setup, the multimodal CanBot was tested in an aerial configuration in which the quadrotor module was utilized for flying locomotion. During the third experimental configuration, the multimodal CanBot was split up into its constituent parts to make the monomodal aerial vehicle featured in figure 3a. This vehicle was tested in an aerial modality for the third experimental configuration. Finally in the fourth part of the experiment, the remaining quadruped module was formulated into the independent vehicle featured in figure 3b and was tested in a terrestrial movement format.

III. ASSESSMENT AND RESULTS

Multiple capture sessions and trajectories were tested for each of the four experimental configurations. The most relevant results have been compiled in this section, and this analysis focuses on situations where the CanBots were moving in broadly linear trajectories. These results were organized in the same order as the previously described experimental configurations, beginning with the multimodal CanBot in the terrestrial modality. Shortened video demonstrations for select portions of this data are also available at [12].

A. *Multimodal Canbot in Terrestrial Modality*

As a convention, the floor of the capture space was marked in blue and black tape. The major black lines indicated a spacing of one meter, while the blue crossed lines indicated a spacing of 25 centimeters. Figure 4 features a time lapse screen capture of the overhead camera where the multimodal CanBot can be seen walking a roughly linear path. The red line represents a rough approximation for the captured MoCap trajectory overlaid on the video images of the actual robot.

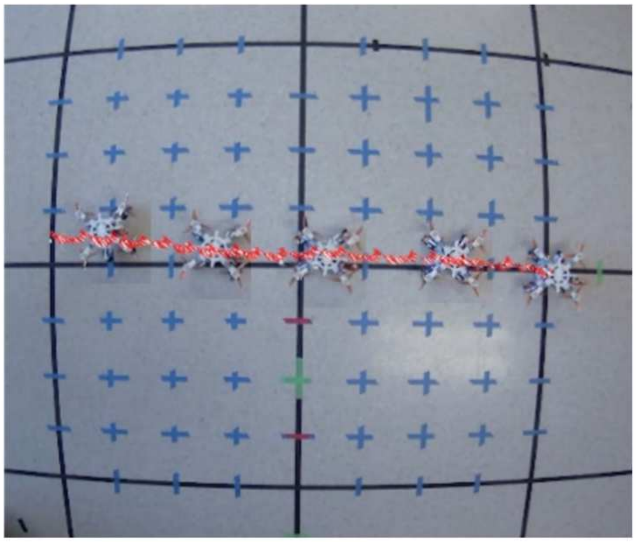


Fig. 4. Actual trajectory of Multimodal CanBot walking in a line as recorded by overhead camera, red line approximates MoCap trajectory capture.

While the perspective of the camera was known to warp the field of view slightly, note that the red MoCap trajectory does broadly align with the actual observed trajectory of the vehicle. To provide common context for the data plots generated by MATLAB, the placement of marking tape was further recreated in the overhead plots of the MoCap trajectories. This can be viewed in figure 5 where the CanBot trajectory, as recorded by the MoCap system, was plotted in addition to the major and minor spacing markers.

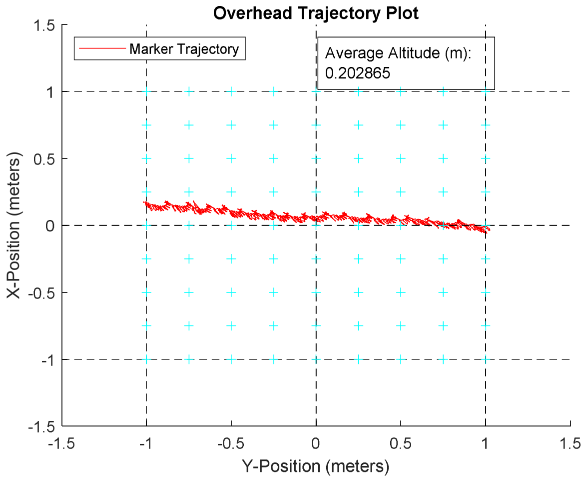


Fig. 5. Plot of Multimodal CanBot walking in a line.

Notably, due to the quadrupedal walking gait, the recorded trajectory for the CanBot shows significant oscillatory movement. A closer inspection of this periodic motion has been included in figure 6.

Fig 6. Zoomed in view of MoCap trajectory for walking multimodal CanBot.

While this motion profile could be confused as noise in the MoCap system, later captures of the aerial vehicles did not exhibit similar data, even when flying near the ground. Additionally, the error rate, as measured by motion capture software Motive, was determined not to exceed 4mm. These errors represent the total possible deviation in the calculated location of the marker arrays and where determined directly by the Motive software. All error plots presented later in this work similarly depict the error in localizing the marker arrays, and do not quantify deviance of the CanBots from the desired straight trajectories. A plot of error for this capture session has been included in figure 7.

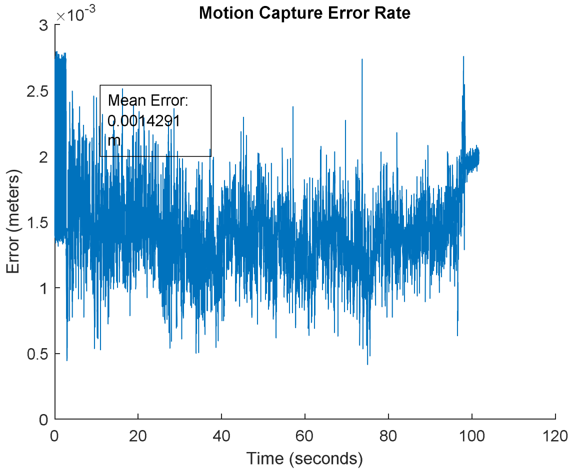


Fig. 7. Error rate of walking multimodal CanBot determined by Motive.

B. *Multimodal Canbot in Aerial Modality*

After completing terrestrial tests, the multimodal CanBot was configured for the aerial modality, and a similar sequence of tests were completed. Figure 8 indicates a relatively straight portion of a test flight conducted with the multimodal CanBot.

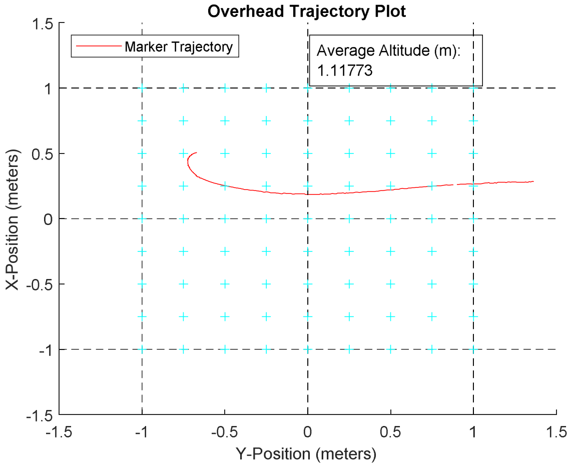


Fig. 8. Multimodal CanBot flying in a straight line.

Notably, the aerial modality for the CanBot represented a significantly faster means for moving the vehicle through the capture space. While in the terrestrial modality, the CanBot required nearly 100 seconds to traverse the two-meter capture field. However, while in the aerial modality, the same two-meter area was covered in less than four seconds. This significant difference in the characteristics of locomotion suggests one of the potential utilities of the multimodal approach.

As before, the MoCap error, measured in meters, was also plotted in MATLAB, as shown in figure 9. This result indicated a mean error of 1.49 mm for this portion of the CanBot tests. Notably, this correlated well with the measurement error recorded for the terrestrial modality of the CanBot which was previously determined to be 1.43 mm. The similarity of the error suggests that the increased speed and altitude of the aerial modality may not have contributed significantly to the MoCap measurement error.

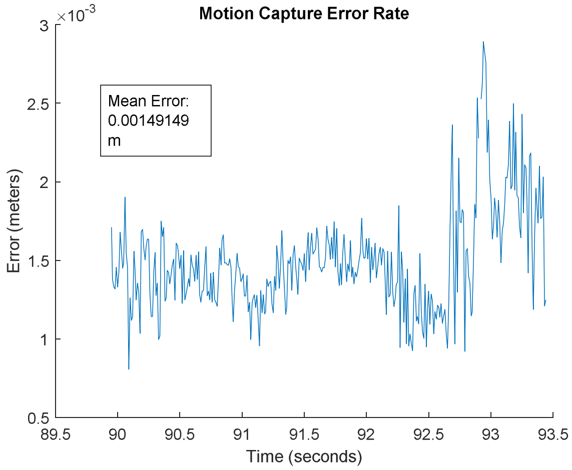


Fig 9. Error of multimodal CanBot flying in a straight line.

C. *Quadrotor Canbot in Aerial Modality*

With the aerial Quadrotor module removed from the multimodal CanBot and configured into a standalone Aerial CanBot, a similar series of tests could be completed. In figure 10, a moderately straight portion of the flight test for the aerial CanBot has been plotted.

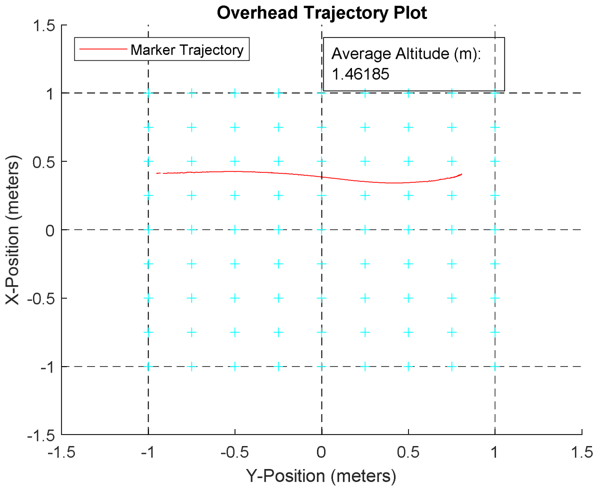


Fig 10. Quadrotor CanBot flying along straight line.

As with the aerial flights of the multimodal CanBot, the monomodal aerial CanBot also generated relatively smooth capture results with minimal recorded error. Figure 11 includes the error plot for the capture period presented in figure 10. The mean error for this section of the test was determined to be 1.57 mm. While these MoCap results for the Aerial CanBot did not indicate any significant difference from those generated for the multimodal configuration, some additional data collection did suggest a difference in locomotion efficiency. Data collected from the onboard Flight Controller (FC) in the Quadrotor Module has been compiled in table I below.

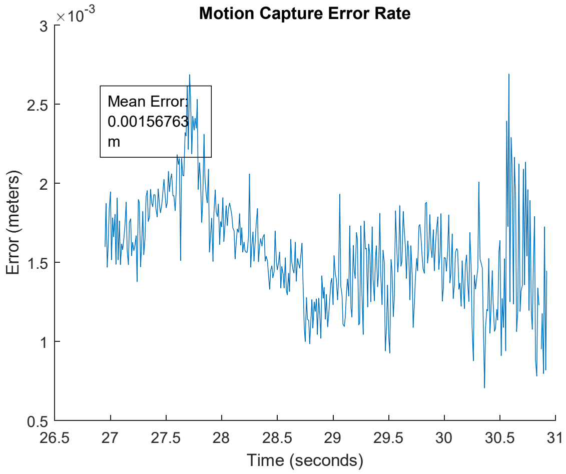


Fig. 11 Error of Quadrotor CanBot flying along straight line.

These results indicate that the peak current consumed by the Quadrotor module was significantly higher for the flight tests performed in the multimodal configuration. When the Aerial CanBot conducted flight tests, the current draw peaked at around 13 amps, while the aerial modality of the Multimodal CanBot required a maximum of 24 amps to operate. These results suggest that the multimodal CanBot requires almost twice as much electrical power to achieve and maintain flight when compared to the lighter Aerial CanBot

TABLE I. AERIAL CANBOT AMPERAGE CONSUMPTION

Vehicle Configuration	**Test Parameters**		
	Vehicle Mass (Grams)	***Flight Number***	***Max Current (Amps)***
Aerial Only	490	A-01	12
Aerial Only	490	A-02	13
Multimodal	698	M-01	24
Multimodal	698	M-02	23

D. *Quadruped Canbot in Terrestrial Modality*

Finally, with the Quadruped Module configured for use as an independent CanSat vehicle, the final battery of motion captures could be conducted. Just as with the previous terrestrial and aerial trajectories, the CanBot was manually driven to follow an approximately straight trajectory. Figure 12 shows the data from this test plotted using MATLAB. Closer analysis of the terrestrial CanBot trajectory revealed a similar periodic motion that was expected because of the walking gait of the robot. However, when the zoomed in view of the CanBot's movement was compared to the same view of the multimodal CanBot, some notable differences were observed. In particular, comparing figure 13, representing the monomodal Quadrupedal CanBot, to figure 6, representing the multimodal CanBot in terrestrial mode, showed that the multimodal CanBot had a considerably less consistent walking gait.

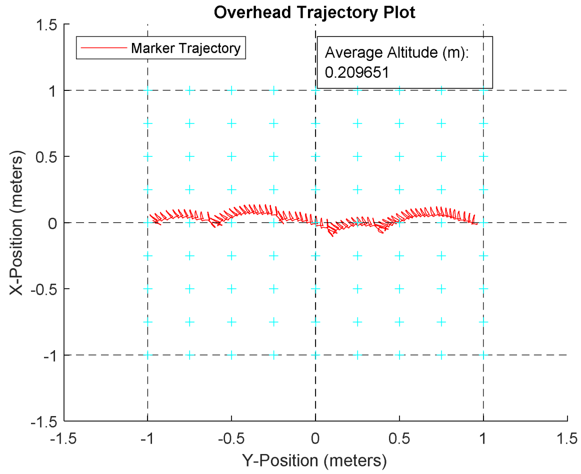


Fig 12. Quadruped CanBot walking along straight line

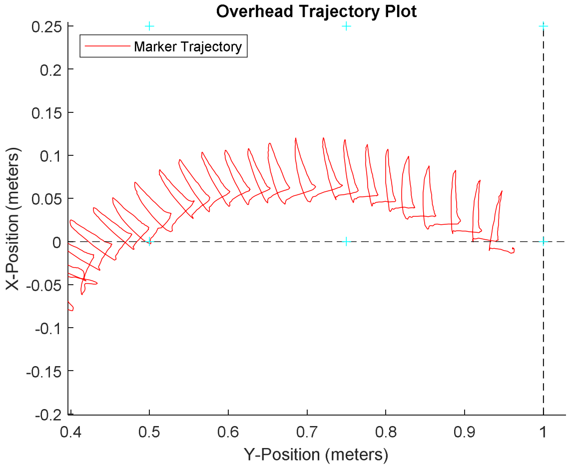


Fig. 13. Zoomed in view of Quadruped CanBot attempting to walk in straight line

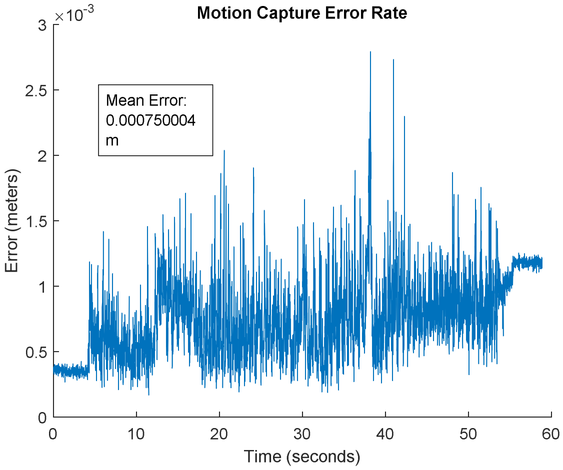


Fig. 14. Error of Quadruped CanBot along straight path

Additional research will be required to identify the cause of this difference, but it was suspected that the additional weight of the multimodal system and a higher center of gravity could be contributing factors. The terrestrial Quadruped CanBot was determined to have a mass of 479 grams, while the Multimodal CanBot weighed approximately 698 grams. Another potentially noteworthy difference involving the terrestrial CanBot includes the mean error rate, featured in figure 14, which was determined to be 0.75 mm for the portion of the test included in figure 12. While this mean error was lower than the other three testing sessions of the CanBots, it is not known if this may have further influenced the consistency of the trajectory plot.

IV. CONCLUSIONS AND FUTURE DIRECTIONS

Although the combination of classical mobility techniques was successfully demonstrated in a prototype multimodal CanBot, the performance of this multimodal vehicle demonstrated marked differences from the distinct monomodal robots. Foremost, in the terrestrial walking locomotion mode, the multimodal CanBot demonstrated a less uniform gait. Instead of the regular periodic motion observed for the terrestrial monomodal CanBot, the tracking data for multimodal CanBot exhibited unexpected oscillations and deviations. And while the motion characteristics of the monomodal aerial CanBot appeared very similar to the motion of the Multimodal CanBot, the energy consumption for the Multimodal system was notably elevated. Ultimately, the optical motion capture system was effective in characterizing the movement characteristics for the monomodal and multimodal CanBots and has aided in understanding potential consequences of the multimodal approach.

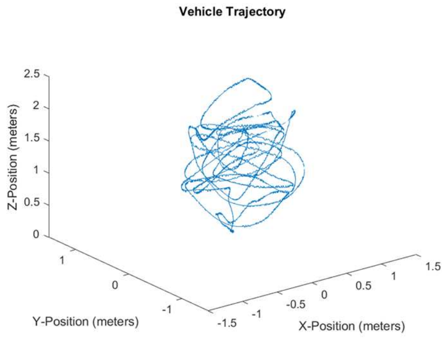


Fig. 15. Full motion Capture data for aerial CanBot

Future expansions of this research will attempt to capture and characterize the effects of transitioning between the terrestrial and aerial modalities in addition to potentially observing hybrid modalities. With a hybrid modality, the CanBot would simultaneously employ both the quadrotor and quadruped mobility modules to improve overall locomotion for complex terrains. Furthermore, while largely straight portions of the capture data were analyzed for the purposes of this work, the entirety of collected data included additional trajectories of greater complexity. An example of the full data capture for the aerial CanBot has been included in figure 15 and shows the complex 3D-dimensional trajectory of the vehicle. Further analysis of this data may also be completed in forthcoming publications.

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