EXPERIMENTAL VERIFICATION OF ROBOTIC LANDING AND LOCOMOTION ON ASTEROIDS

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ABSTRACT

In-situ explorations of asteroids and other small celestial bodies are crucial to collect surface samples, which could be the key to understanding the formation of our solar system. Studying the composition of asteroids is also important for future planetary defense and mining resources for in-situ utilization. However, the weak gravitational field poses many challenges for robotic landing and locomotion scenarios on the surface of asteroids.

Legged climbing robots are expected to perform well under microgravity, as they can maintain surface attachment, preventing undesired flotation and uncontrolled bouncing [1]. Therefore, we need to consider methods to plan and control the landing and locomotion of climbing robots on asteroids. In this study, we have performed experiments regarding the emulation of two scenarios; 1- Landing, 2- Locomotion. For both landing and locomotion scenarios, separate PD controllers have been utilized.

Key words: Orbital scenario emulation, orbital robotics, landing and locomotion on asteroids, floating platform, pneumatic levitation.

1. INTRODUCTION

We propose an experimental evaluation of landing and locomotion planning and control methods, using an air-floating platform to emulate two-dimensional microgravity environments [2, 3, 4, 5, 6]. Floating platforms have pneumatic equipment mounted beneath the structure, named "air-bearing". Air-bearings blow high-pressure air toward epoxy floor to cut mechanical contact between air-bearings and epoxy floor, which creates vertical pneumatic levitation. After achieving the vertical levitation, nozzles are used to create 2D motion on epoxy floor.

The experiments have been conducted in SnT-University of Luxembourg's Zero-G Lab (as known as Orbital Lab), Kirchberg, Luxembourg [7, 8, 9, 10, 11, 12]. This facility has a super-flat epoxy floor (3 m×5 m area) on which the floating platform performs. It has been utilized to emulate on-orbit scenarios such as spacecraft proximity maneuvers, rendezvous, on-orbit maintenance *etc*. Moreover, it can be used to generate datasets and to verify and validate closed-loop control approaches. There are many similar facilities established in various points of the World [13, 14, 15, 16, 17, 18, 19].

The CAD model of the SpaceR's floating platform is given in Fig. 1. Due to its carbon-fiber based lightweight structure, the design of the SpaceR's floating platform provides modularity and increases endurance. Its total weight is 10.95 kg when the compact air bottle is full. It has four air-bearings and eight nozzles. The robotics arms (Pincher Robot Arm Kit [20]) are used for locomotion (total two) and their drivers are assembled on both sides of the floating platform. Each robotic arm has five Degrees of Freedom (DoF) consisting of servo motors, including its gripper. The following sections describe the landing and locomotion approaches. In the second section, the results are discussed. In the third section, the conclusion is given. In the forth section, the potential future works are mentioned.

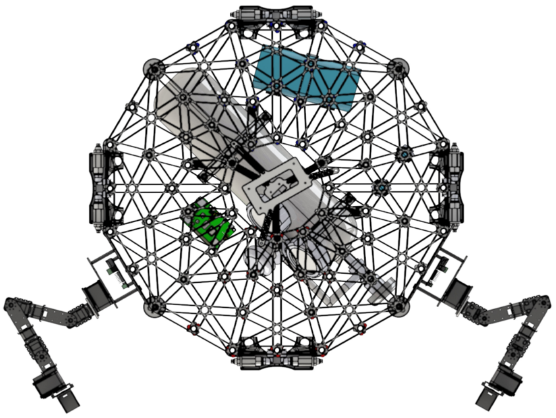


Figure 1. CAD model of the SpaceR's floating platform

1.1. Landing

For the experimental emulation of the landing scenario, we assume our robotic platform with air thrusters to control the position and attitude necessary to achieve landing on an asteroid. A PD controller is used to realize the motion control of the floating platform, using the Ziegler–Nichols method as a heuristic method of tuning PD parameters. The tuning is utilized to minimize overshoot and rise-time. D parameter of the PD controller is merged with the low-pass filter to suppress unexpected peaks in the feedback data. The Motion Control System (MCS) uses sensory feedback at a frequency of 240 Hz for the closed loop, employing the extended Kalman Filter to deal with the noise in the MCS data. Since the floating platform has 3-DoF, a separate controller is assigned for each DoF. The landing and locomotion scenarios are sequential, therefore the locomotion operations begin after the landing is securely achieved.

1.2. Locomotion

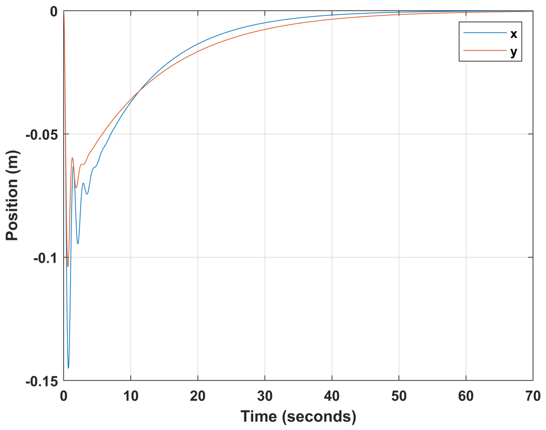
Experimental evaluation of locomotion is made using the same floating platform, with two robotic arms with grippers to emulate the climbing motion in two dimensions. The robot can achieve continuous mobility by moving each robotic arm to grasp the next target on the emulated surface, followed by the arms' movement to drag the main body forward. The motion planning for the climbing robot aims to reduce the contact forces that could cause the grippers to detach from the surface, using reaction-aware motion planning [21].The swinging trajectory of the legs is constrained to a smooth polynomial curve and optimized to minimize the change in the generated momentum, reducing the induced motion reactions [22]. The optimization problem is shown in Eq. (1), to find the optimal coefficients $\boldsymbol{A}_{Bj}$ for the feasible polynomial curve to minimize the momentum change $\dot{\boldsymbol{\mathcal{L}}}$.

$$
\begin{aligned}
\min_{\boldsymbol{A}_{B3},\boldsymbol{A}_{B4}} \quad & \max\left(|\dot{\boldsymbol{\mathcal{L}}}|\right) \\
\text{s. t.} \quad & \boldsymbol{x}_e(t) = \sum_{j=0}^{7} \boldsymbol{A}_{Bj} B_i(t) \\
& \phi_{\min} \leq \phi(t) \leq \phi_{\max}
\end{aligned}
\tag{1}
$$

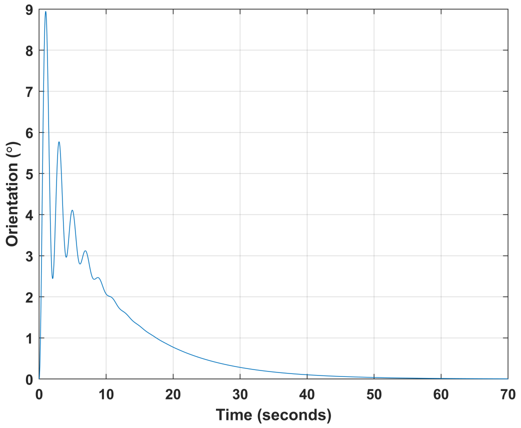
Additionally, we compute the base motion that distributes the momentum generated by the swing motion to the robot's whole body, minimizing the reactions during the swinging phase. With the definition of desired poses for the robot base and legs, we use a PD controller for the legs' motors after computing the desired joint angles from inverse kinematics.

2. RESULTS

A pose control experiment using the floating platform was performed to emulate landing, from an initial pose [0 m, 0 m, 0°] to the set-point [0.3 m, 0.3 m, 20°].



(a) Position (m)



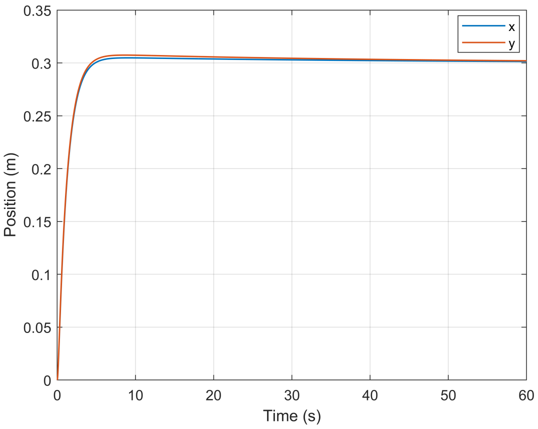
(b) Orientation (°)

Figure 2. Disturbance rejection simulation results

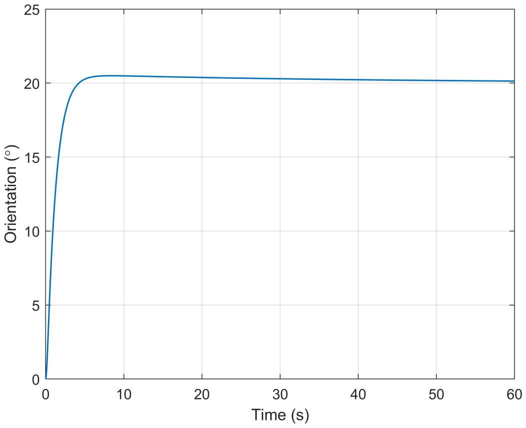
The disturbance rejection property of the proposed controller is given in simulations shown in Fig. 2. For translational axes, 1 N disturbance is applied. For orientation axis, 1 Nm disturbance is applied. The position control simulation results are given in Fig. 3.

The position control preliminary experimental results are given in Fig. 4. The experimental data given in Fig. 4 shows that the controller satisfies asymptotic stability and convergence goals.

For the locomotion experiment, we placed the robot using both grippers to grasp the targets on the wall to emulate the asteroid's surface. We computed the desired trajectories for the legs and base offline, executing a feedforward PD control for the joints to drive the robot toward its goal. The result for the locomotion and an image to illustrate the experiment are shown in Fig. 5.



(a) Position (m)



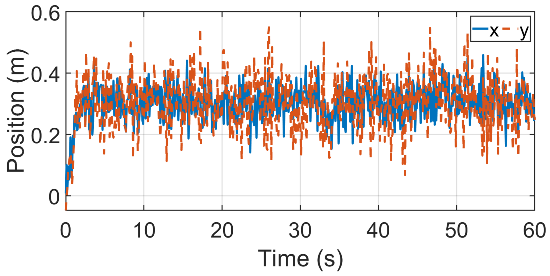
(b) Orientation (°)

Figure 3. Position control simulation results for landing

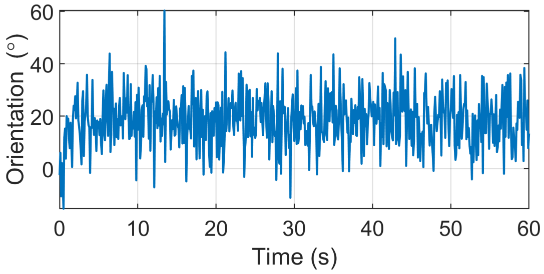
Using the MCS available in the facility, we measured the robot's position, resulting in a total travel distance of approximately 10 cm, the same as planned offline before the experiment. Although the robot's position tracking did not fully match the planned trajectory, no significant issues happened, such as gripper detachment or slippage, and the robot successfully reached its goal position.

3. CONCLUSIONS

Considering the scenario of a legged climbing robot exploring an asteroid, we propose a strategy using a pose control for landing and reaction-aware motion planning for locomotion. Both methods were verified experimentally using an emulated microgravity facility, achieving the desired results for landing and locomotion. Using the proposed methods, the accuracy of the experimental results makes the floating platform a successful landing and locomotion emulator that can be used in orbital laboratories.

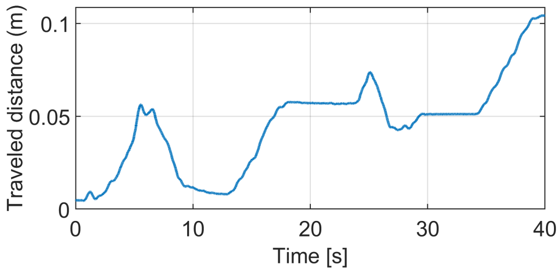


(a) Position (m)

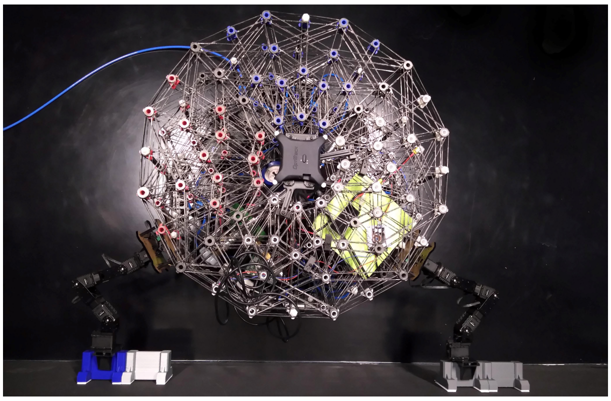


(b) Orientation (°)

Figure 4. Position control experiment results for landing



(a) Traveled distance (m)



(b) Robot walking experiment

Figure 5. Traveled distance experiment result for locomotion

4. FUTURE WORKS

From both software and hardware perspectives, there are ongoing studies that focus on making the floating platform a whole landing and locomotion emulator for microgravity environments.

APPENDIX

General overview video of Zero-G Lab, ”The Zero-G Lab: Testing in Micro-Gravity Environment”, can be watched from this link. A demonstration video regarding the floating platform, ”Floating platform: Micro gravity emulation in 2D”, can be watched from this link.

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