Advancing Robotic Anchoring with Intelligent Load Distribution

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***Abstract*—Rock climbers and asteroid landers alike rely on effective load distribution between their limbs and foot pad to avoid overloading any single point and remain anchored. For a robot to maximize its anchoring force, it must intelligently distribute its load across anchors of different strengths. However, this requires accurate prediction of an imminent anchor failure. Optimal load distribution allows the robot's total anchoring force to be the sum of each anchor's maximum instead of a multiple of the weakest anchor's strength. In our work, we introduce an optimized, real-time failure prediction method to detect the impending failure of a geotechnical anchor and allow a robot to best distribute its load among multiple anchors. We experimentally demonstrate that our load distribution method increases the total anchoring force to 97% of its maximum possible strength, compared to 75% without load sharing. This method could be used to bolster the anchoring efficiency of future asteroid landers and low-gravity mining robots.**

I. Introduction

A skilled rock climber instinctively understands the strategy of weight distribution: bearing more body weight on a strong foothold while minimizing the load on a tenuous finger grip. This heterogeneous load sharing across unequal limbs helps the climber avoid overloading any one hold and losing grip. A similar method may be used by a mining robot or asteroid lander to distribute its load between many grippers or anchors to keep it fixed to the ground.

Optimizing such a robot's anchoring force is a complex task: even if the anchors are designed the same, their hold in the ground may vary with uneven geotechnical conditions. The challenge arises when the robot must accurately identify when an anchor is about to fail. Such prediction is crucial for a robot to optimize the load on its anchors, which then ensures maximum potential strength. The overall anchoring force then becomes the sum of each anchor's maximum load, rather than a multiple of the weakest anchor's strength.

In our work, we introduce a simple, optimized method of real-time failure prediction that detects when a geotechnical anchor is about to fail and allows a robot to distribute its force among several anchors most effectively. We first present the working principles of distributed loading and failure prediction, then our experimental methods and parameter optimization, and last the results showing the anchoring improvement.

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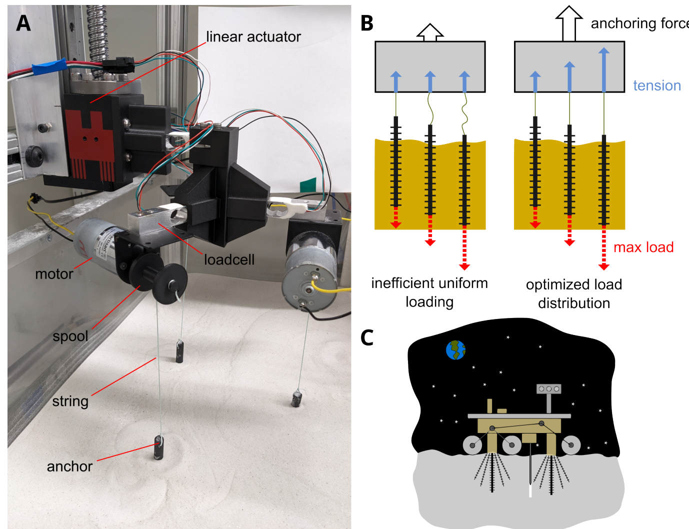

Fig. 1. **(A)** Experimental system with intelligent load sharing among three geotechnical anchors. **(B)** Loading anchors uniformly provides less total anchoring force than loading each anchor to its maximum load. **(C)** We envision that intelligent load sharing will be implemented on low-mass asteroids and lunar landers to maximize their ability to apply forces on alien surfaces.

II. Working Principles

A. Distributed Loading

To maximize total anchoring force in a multi-anchor system (Fig. 1(A)), it is crucial to share loads heterogeneously between anchors with different capacities. If all anchors were loaded uniformly, they would fail sequentially from weakest to strongest, with poor overall anchoring force. Instead, our method preloads each anchor to just under its maximum capacity, ensuring the combined anchoring force is the sum of each anchor's maximum (Fig. 1(B)).

B. Anchor Failure Prediction

Using the first derivative of force and time data, our algorithm predicts real-time anchor failures. As an anchor is loaded at a constant rate, its force vs. time profile culminates in a clear peak before declining, which typifies the impending anchor failure. Our algorithm detects this imminent peak by tracking when the force-time derivative begins to drop. As shown in Fig. 2(A), when the derivative decreases to some fraction of its maximum, we stop loading the anchor, thereby preloading the anchor to its maximum force.

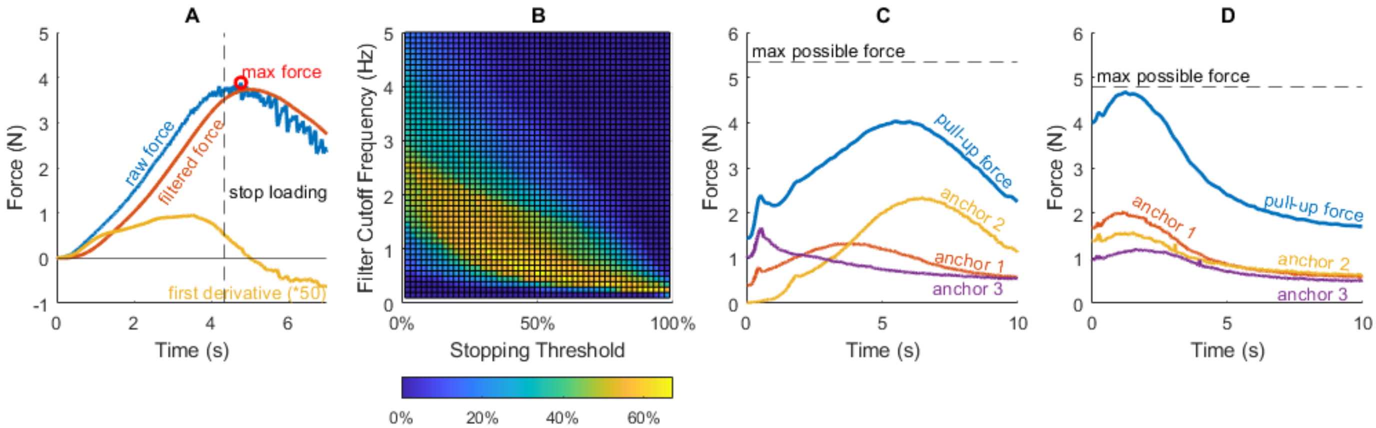

Fig. 2. **(A)** Using the derivative for force vs. time on an anchor as it is loaded, we can predict when an anchor is about to fail. **(B)** Using experimental training data, our MATLAB simulation shows which algorithm parameters most effectively predict peak anchoring force. **(C)** Without distributed loading each anchor peaks at a different time. **(D)** With intelligent distributed loading each anchor peaks synchronously, increasing the total anchoring force.

III. Experimental Methods

A. Test Setup

Our test setup consists of three geotechnical anchors positioned in a sand bed (Fig. 1(A)). These 3D printed cylindrical anchors are 8.5 mm in diameter and 10 cm long, with 5 mm long, 3 mm wide protrusions spaced every 10 mm in four rows along its length. A motorized spool preloads the anchors at 2 mm/s via a string, with a load cell connected to measure pretension and anchoring force. The anchors are arranged in an equilateral triangle and attached to a linear actuator and load cell to measure the total anchoring force. An Arduino Uno records the load cell data and controls the motors. The sand container is 30 cm deep, 40 cm wide, 60 cm long, and filled with dry play sand. With air fluidization and vibration, sand is mixed between trials and as the anchors are placed.

B. Anchor Failure Prediction Algorithm

Our algorithm uses filtered force and time data to predict anchor failure and efficiently preload the anchors. The anchors are preloaded until the first derivative declines to an experimentally optimized threshold percentage P_{tr} of its maximal value.

1) Smoothing Filter Design: Because the derivative is susceptible to noise, we use a Butterworth filter to smooth the force data in real-time. We used a second-order filter with a f_s of 67 Hz determined by our load cell amplifiers and an experimentally optimized cut-off frequency f_c.

2) Parameter Optimization: Using 30 trials of experimental training data and a MATLAB simulation, we optimized P_{tr} and f_c by maximizing the percent of trials that would have accurately stopped preloading within 10%, but not over, the maximum anchoring force. Our results in Fig. 2(B) identified the optimal parameters as $f_c = 0.5$ Hz and $P_{\text{tr}} = 49\%$.

C. Distributed Loading Experiment

To assess our method's efficacy, we measured the anchoring force on our system with and without the algorithm in play. In the naive control case, the linear actuator pulled out three buried anchors from the sand while measuring force (Fig. 2(C)). In the optimized load distribution case, the anchors were first preloaded using our algorithm, then pulled out to measure their load (Fig. 2(D)). One trial of each test from several trials conducted is plotted.

IV. Results and Discussion

As a result, our load distribution method notably increases the anchoring force of our multi-anchor system. Our optimized strategy synchronized the anchors' force peaks, capturing up to 97% of the total possible force. In contrast, the non-optimized approach revealed scattered peaking across anchors, reducing the anchoring force to 75% of the maximum. Further trials will statistically show its improvement and assess its performance in a variety of mediums including compacted sand and lunar regolith simulant.

V. Visions

With the dawn of more affordable space travel, both NASA and private programs are poised to further extraterrestrial exploration. We envision our methodology playing a pivotal role in applications such as asteroid mining, lunar drilling [1], and Martian sensor deployment [2].

In the coming decade, advancements in AI and computation promise to redefine subterranean robotics: AI development will facilitate precise terradynamic modeling and simulations, streamlining the design of efficient anchoring and burrowing robots. This integration will shape our exploration from Earth's underground world to alien realms.

References

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