Lemur IIb: a Robotic System for Steep Terrain Access

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Abstract

To extract the full science potential from planetary surface operations, robots must be able to access the entire surface of the planetary body, not just the relatively level areas. Buoyed by the success of *top-to-bottom* strategies employing tethered robots, the stage is set for *bottom-to-top* technologies and techniques to be investigated. To this end, we have designed and built ***Lemur IIb***, a 4-limbed robotic system that is being used to investigate several aspects of climbing system design including the mechanical system (novel end-effectors, kinematics, joint design), sensing (force, attitude, vision), low-level control (force-control for tactile sensing and stability management), and planning (joint trajectories for stability). The technologies developed on this platform will be used to build an advanced system that will climb slopes up to and including vertical faces and overhangs and be able to react forces to maintain stability and do useful work (e.g., sample acquisition/instrument placement). Among the most advanced of these technologies is a new class of Ultrasonic/Sonic Driller/Corer (USDC) end-effectors capable of creating "holds" in rock and soil as well as sampling those substrates. This paper lays out the mechanical, electrical, and algorithmic elements of the ***Lemur IIb*** robot and discusses the future directions of development in those areas.

Keywords: climbing, steep terrain, drilling, autonomy, force control

1 Untethered Climbing of Steep Terrain

The creation of a robotic system that will actively cling to vertical or overhanging slopes (i.e., achieve force closure relative to the terrain) requires three areas of development: an end-effector capable of using or creating handholds in various substrates, a robotic platform with sufficient dexterity to properly place those end-effectors, and the force-control and planning algorithms necessary to direct the platform's actuators. In particular, hard-real-time problems of synchronized joint movement are exceptionally acute in limbed systems due to the need for highly coordinated motion within a limb and across multiple limbs (starting, stopping, and smooth motion in between). Moreover, the grouping of the coordinated actuators is constantly changing based on gait requirements. Exacerbating the problem are large numbers of actuators (DOFs), intermittent contact, and over-constrained static and dynamic conditions. The problem becomes even more challenging for the operational regime of a free-climbing system in that active force-control for anchoring and stability increases the required level of coordination and synchronization.

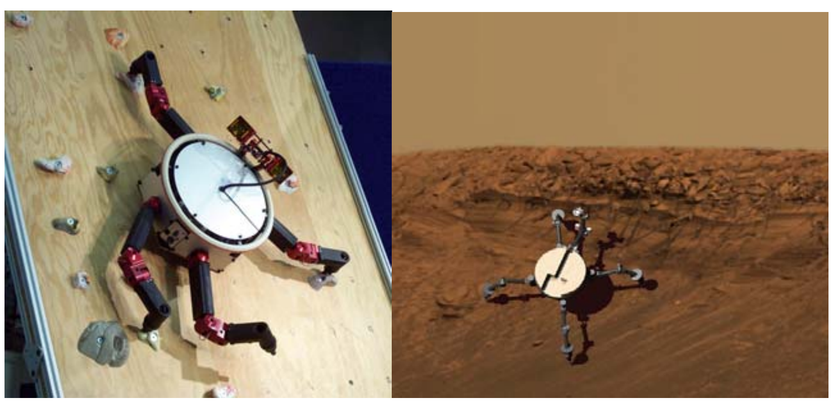

Fig. 1. LEMUR IIb on climbing wall and (conceptually) on Endurance crater

2 Other Robots Relevant to the Lemur IIb Concept

Robots that compare to the Lemur IIb fall into three distinct areas: gravity-stabilized legged and wheeled robots, tethered robots, and robots that adhere to the substrate. The first category is best represented by MER at JPL and DANTE I (CMU) [1], outside of JPL. The second category is characterized by the Cliffbot system at JPL [2] and DANTE II (CMU) [3]. The third category covers MACS at JPL, Ninja-1 [4] and the Gecko robots at iRobot.

The robots in each of these categories cover some portion of the operational envelope of the Lemur IIb. In the first case, the gravity-stabilized robots can traverse over rough terrain. However, these vehicles become unstable on slopes on which gravity becomes a *destabilizing* factor, approximately 45-55 degrees from horizontal. The tethered systems overcome this limitation by counteracting the destabilizing force of gravity with tethers attached to anchors at the top of the slope. This solution itself creates a limitation due to the fact that the traverse must begin at the top of the slope. In addition, the tethered robot may loose contact with the substrate (and thus a level of controllability) when an overhang is encountered. An encounter with an overhang may also result in a non-reversible path. The third category relies on active or passive adhesion of the robot to the substrate, generally performed by suction cups, magnets, or sticky adhesives. Each of these adhesion methods applies to a very narrow range of substrate properties, primarily smooth, clean, non-friable surfaces (plus ferrous in the case of magnetics). While these techniques are useful for certain scenarios, those scenarios do not as a rule exist for space exploration.

Some of the climbing robots have been developed utilizing contact with the terrain are [5-7].

3 Lemur IIb Platform Overview

The Lemur IIb platform is, with few exceptions, identical to that of Lemur IIa. The joint design, chassis, electronics, and infrastructure software are all shared. Please see [8] for a more complete description.

Table 1. LEMUR IIb system overview

Mass (kg)	8
Limbs	4
Degrees of Freedom	12
Actuator count (max)	13
Processor speed (MHz)	266

The major divergence lies in the kinematic layout. In an effort to make the challenges of free-climbing more tractable, the decision was made to restrict initial investigations to the planar problem. In fact, the usual task board is a segment of a gym climbing wall, shown in Figure 1. Given this simplification, the kinematic layout of Lemur IIb was altered from that of Lemur IIa. Kinematic differences include:

- 4 limbs (rather than 6) for decreased system mass and complexity
- 3 degrees-of-freedom per limb (rather than 4) for decreased mass per limb
    - Yaw, Yaw, Pitch (rather than Roll, Yaw, Pitch, Pitch)
- each limb is 25% longer than the limbs of Lemur IIa to increase the reach

These differences result in a platform that is less massive and with a center of gravity closer to the surface of movement, while retaining all of the load carrying capacity. Thus, it will be a more capable platform for climbing inclined planar surfaces.

4 Climbing End-Effectors

Three different approaches of differing maturity have been taken with Lemur IIb's end-effectors. The end-effectors that have been using in testing so far have been variants on a simple peg. Of greater eventual utility are Ultrasonic/Sonic Driller/Corers (USDC) that can be used to create handholds. Possibly even more ambitious are end-effectors based on equipment used by human sport climbers.

The peg end-effectors come in two flavors: simple peg and self-centering peg. With rubberized contact patches, these pegs provide sufficient friction for testing on inclines up to ~60°. The self-centering peg is a wedge whose apex edge is collinear with the passive wrist axis (normal to surface plane. Contact with a hold causes the wedge to center, but any further self-movement of the robot will not cause any translational errors, unlike a simple round peg.

Due to the advantages of the USDC (*viz*., simple design, low normal force during operation, dual use for mobility and sampling), this apparatus was chosen as the basis of the drilling end-effector design. In addition, the vibratory nature of the USDC can be used to improve purchase in loose materials.

The USDC is designed for three purposes. First, it had to drill into rock with minimal chance of becoming stuck. Second, it must support the weight of the robot when acting as an anchor. Last, it must be useful in loose scree and other non-hard rock substrate. The ability of USDCs to drill into rock has been well demonstrated, but the added desire to minimize the risk of being stuck prompted a redesign that enables the USDC to *hammer out* as well as hammer in. The second requirement drove a new design for the USDC bit that allowed it to act as a cantilevered beam when taking up the weight of the robot. This represents the worst case loading condition. The final requirement did not require any change in the USDC design, but did drive the design of the external housing. Through testing, the ability of the USDC to bury itself in loose material was established. The housing, then, was designed to act as a combination "sand anchor" (with longitudinal vanes) and a "ski-pole basket" (with a transverse plate). To date, the climbing-specific USDC has been tested in various materials and the drill rates and breakout loads established. In addition, the penetration depth versus force required for various loose materials has been determined. For greater detail on the design and testing, see [9].

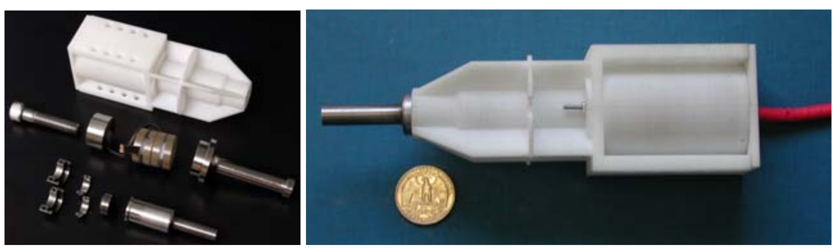

Fig. 2. USDC

Emulation of already proven equipment intended for human climbers can provide positive attachment of robots with less operational time and energy than the drilling method. Currently a show-and-tell prototype has been designed and fabricated that incorporates a plain hook and a cam hook (both standard climbing items) into each of three "fingers".

The overall assembly can be used for a range of holds:

- Any of the three hooks can be used for horizontal ledges
    - remaining fingers provide in-plane moment support
- The cam hooks work in non-horizontal cracks or slit features
    - Regular hooks are spring loaded, and will move out of the way of the cam hooks
- The linkage driving the fingers can also be made to emulate a "cam", which is a self-locking piece of equipment for pockets or wide cracks

Fig. 3. End-effector for robotic climbing

5 Operational Algorithms

Consistent with the task of steep terrain mobility, two algorithms have been implemented on the LEMUR IIb robot.

5.1 Motion planning for robotic climbing

Recent developments in motion planning [10,11] have enabled the LEMUR IIb robot to traverse the climbing wall shown in figure 1. This planner determines the route through the terrain and the hold-to-hold motions that maintain the robot in static equilibrium.

5.2 Hold characteristic identification using tactile sensing

The above-mentioned planner requires the *a priori* knowledge of three terrain features: contact location, surface normal and coefficient of friction. In application, the robot must acquire the properties of the holds via on-board sensors. Vision-based sensor approaches are inadequate since the surface of interest is often occluded from view. Figure 4 compares the true shape of the hold to an image taken by the robot's left stereo camera.

To this end, we have developed a tactile sensing approach to discern three characteristics of the hold. The kinematics of the LEMUR IIb localizes the hold. The shape of the hold is found by dragging the end-effector along the contour. Lastly, a force-torque sensor measures the contact forces to resolve the coefficient of friction. In operation, a new hold is sensed while three limbs in contact with the terrain support the robot.

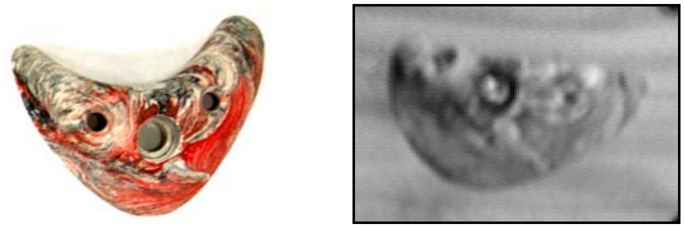

Fig. 4. Top view a hold (left). View of the hold from the on-board camera (right).

A planner has been developed to determine maximum allowable contact load at the target hold that maintains the robot in static equilibrium. The output of this planner is used to set an upper limit for the hold sensing contact force magnitude.

The "free" limb performs the hold sensing via a hybrid force-motion controller. The controller is similar to the work done by Yoshikawa [12]. One distinction is that the manipulator is mounted to a mobile robot and operates quasi-statically. The two technical challenges for this operation are the implementation of force control on manipulator with highly geared, non-back-drivable joints, and contour following with the presence of high surface friction.

Preliminary results show that the LEMUR IIb limb can sense holds while maintain an average contact force of 3 Newtons and regulating the peak load under 5.1 Newtons. Additionally, the calculated friction coefficients have standard deviations less than 0.09.

6 Conclusions and Future Work

The LEMUR IIb robot allows the investigation of the technical hurdles associated with free climbing in steep terrain. These include controlling the distribution of contact forces during motion to ensure holds remain intact and to enable mobility through over-hangs. Efforts also can be applied to further in-situ characterization of the terrain, such as testing the strength of the holds and developing models of the individual holds and a terrain map.

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