

Robotic Rock Climbing using Computer Vision and Force Feedback

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Abstract Climbing robots that climb flat structures using suction cups or magnets are commonly described in the literature. However, robots that can autonomously find randomly placed handholds, and then plan and climb a route up the walls using those handholds, have not been described. A low cost robot has been designed by Dartmouth College students to climb a near-vertical indoor climbing wall using computer vision to locate handholds, and force feedback to maintain pressure on handholds. Using a variation of the probabilistic roadmap algorithm, a climbing route up the wall is planned and then executed.

Keywords: *mobile robots, path planning, computer vision*

Introduction

Development of autonomous robots that climb a rock-climbing wall is a logical extension of existing work in the field of mobile robots. Rock-climbing walls can be either artificial indoor walls or natural outdoor walls. The robot climbs a route up the wall by using the available handholds to both pull and push itself up the wall in a sequence of quasi-static movements. Because an indoor wall can easily be constructed in any robotics lab, this problem domain can become a test platform for algorithms in intelligent control, sensor-data fusion and path planning.

Currently, one of the worlds most sophisticated, both mechanically and algorithmically, four-limbed robots is the Sony's Qrio [13, 15]. It is the first robot that can run, and pick itself up if it falls, but it has not yet been taught how to rock climb.

This paper describes *Tenzing*, a four-limbed rock-climbing robot, designed by a team of computer science and mechanical engineers in the Spring of 2004 at Dartmouth College. *Tenzing* currently uses a conservative climbing strategy and climbs like a novice human who is afraid to fall. Using a path planning algorithm that connects together stable stances, *Tenzing* is able to autonomously ascend a near vertical climbing wall.

Background

Climbing robots were initially designed to climb structured environments. Robots were built to climb walls of nuclear reactors, glass of high rise buildings and oil tanks using suction cups [4, 5, 11, 12], the steel plates of boilers using magnets [6], ropes and pipes [14] and the steel structure of a bridge using grippers [1]. The structure of these environment constrained the mechanical construction of the robots,

while the uniformity of the environment allowed for a solution that relied on a repetitive gait. Using inspiration from nature, mechanical solutions included inch-worm, caterpillar [18], spider [12] and a biped-based designs [16].

Most of these climbing robots require a smooth surface to climb, and the robots use suction cups and magnets to gain purchase on an otherwise smooth surface. Much like when humans climb ice, with the appropriate gripping tool (an ice axe for humans), every location provides a handhold. These robots, therefore, did not have to search for handhold, and plan a path using only the available handholds.

Most indoor rock-climbing walls are constructed from sheets of plywood, and are pre-fitted with T-nuts that allow handholds to be quickly bolted, and unbolted, from the wall. *Routes* that ascend the wall can then be easily created. Climbers find routes interesting when they use a variety of body of positions and when the routes pose some type of planning puzzle.

Such a wall is climbed by LEMUR from the Jet Propulsion Laboratory[2, 3]. Lemur is a four-limbed robot inspired by the spider-model, with each limb having have four degrees of freedom, connected to a round body in a rotationally symmetrical design. LEMUR uses planning based on a Probabilistic RoadMap (PRM) algorithms designed by Tim Bretl of Stanford's Aerospace Robotics Lab. As shown in videos from the project website, LEMUR can, with coaxing, slowly ascend an artificial climbing wall.

During the spring of 2003 students at SUNY Plattsburgh designed a planar robot that could climb a near vertical artificial climbing wall. Handholds and the robot were located using computer vision. Performance was compromised because there were no sensors measuring contact pressure of the robot's hands on the handhold.

Path Planning

Robotics path planning is considered a hard problem and to achieve computational feasibility many researchers have relied on stochastic sampling to achieve good performance. The most popular of these techniques are variations of the *Probabilistic RoadMap* (PRM) algorithm [8], including the variation used by the Stanford climbing robot.

PRM generates a graph in Configuration-space, the C-space, for use as a roadmap in two stages. The first stage finds the nodes of the graph which correspond to feasible robot configurations using some stochastic sampling strategy. Next, the nodes are connected using a local planning algorithm. Connections are limited to nodes that are found to be relatively near to each other, using some distance metric. Then a global planner searches for a sequence of motions

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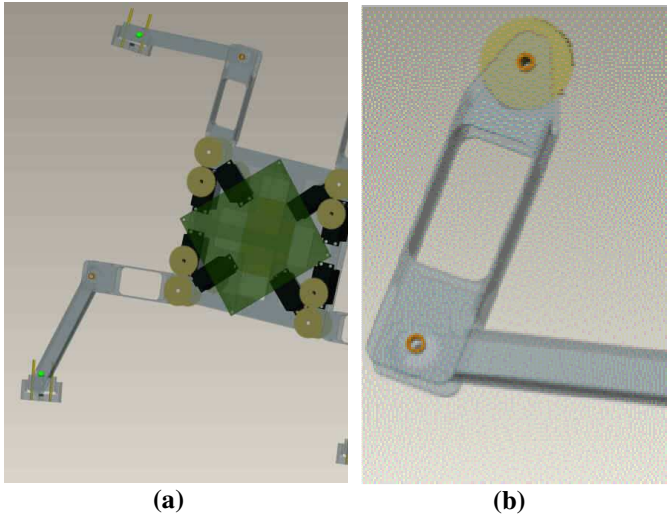


Figure 1. The pro-engineer generated drawings of the robot (a) and a detailed drawing of the arm (b). The belt used to articulate the elbow/knee is not shown.

that move the robot from the start position to the end position.

Much of the literature on PRM focuses on either moving rigid objects in cluttered environments or moving a robotic arm to achieve some task. PRM has difficulties in both problem domains when narrow passages exist in the configuration space [7]. Purely random sampling may not find the narrow connection between two well-connected regions.

Grid-based methods are also used in path planning and are favorably reviewed by LaValle [10]. LaValle shows that a grid-based approach can achieve a computationally tractable solution without relying on purely stochastic process for picking nodes on the road map.

PRM has also been applied to a closed chain system like a climbing robot. A common example of a closed chain system is when two robots cooperate in picking up a single object[9, 17]. This is equivalent to a climbing robot standing up on two footholds while maintaining contact on each foothold.

Problem Formulation

A robotic climber stands before a route at the base of the climbing wall and searches for a sequence of moves that will form a secure path to the top. With only the information provided by vision, it plans a route up the wall. Then allowing for inaccuracies in sensing and actuators, the robot ascends the route autonomously.

The robot climber should also access the stability of planned climbing positions and the feasibility of moving a hand to a new handhold without falling. By providing a cost function that can be optimized through learning, the risk of the robot falling while ascending the climbing route should be gradually reduced.

Solution Statement

Climbing a route up a wall using a set of arbitrarily placed handholds requires a plan. By necessity a human climber will find a global solution by first partitioning the route into smaller sections or patches and then finding a plan for each of the small patches. After finding a set of patches

that overlap all the way to the top, the climber attempts to visualize the path up the entire route that links the patches. Some sections of the climb will be considered easy and no detailed plans for these sections are made, the patch is effectively chunked for later evaluation so to simplify the overall path planning. This can be because there are either numerous handholds, allowing for many possible solutions, or because the handholds that are seen, appear large and spaced at a reasonable distance and pattern.

Other sections of the routes can be perceived to be tricky because there are either only small handholds, or the large handholds that do exist are too far apart or place in an awkward pattern. Climbers then will formulate details for these sections because of the high risk of falling in these sections. If no reasonable sequence of moves can be found through a difficult patch the climber will change the route, trying perhaps to go a little more to the left or the right.

Once the climber begins climbing, the planned route must be continuously adapted based on the new perception of the robot. Some handholds may not be as good as they appear from the ground; some may now appear to be better choice. At other times perhaps the robot can not span the distance between holds because it is not able to keep pressure on the remaining three handholds when reaching for a new handhold. This sensor data fusion problem is at the heart of the complexity of the climbing task. We present here a planning algorithm similar to the Probabilistic Road Map method to solve this task.

However, dexterity in climbing requires more than just visual acuity and good planning. The robot must be able to sense the spatial orientation of the robot relative to the neighboring handholds and sense the applied forces on the holds. A human climber uses a complex perception of forces and torques to sense when the climber is in a quasi-stable position, and thus learn the set of stable positions and climbing movements. With practice, the climber will be able to accurately predict the risk of falling for any short sequences of moves.

Robot Description

Tenzing was designed as part of a ten-week academic course in the spring of 2004. A team of six mechanical engineering students designed the mechanical robot, six students worked on the embedded software, and another six students worked on the path planning, image processing and graphical simulation.

Mechanical Design

Tenzing was built from aluminum, Figure 1, using standard stock. Because of the time constraints, the mechanical complexity of Tenzing was reduced by having the robot operate only in 2-dimensions. Mechanical power comes from eight Futaba S3802 hobbyist servo-motors that gave approximates 1.7 degree resolution. Each motor generates 11 kg/cm of torque. As shown in Figure 1 all eight motors are mounted on the rectangular body, which is 8-inch square. The shoulders and hips are gear driven and are at the corners of a 7-inch square centered on the body. The robot body has a thickness of 3" and a clearance from the climbing wall of 7/8". The knees/elbows are articulated by a belt that runs

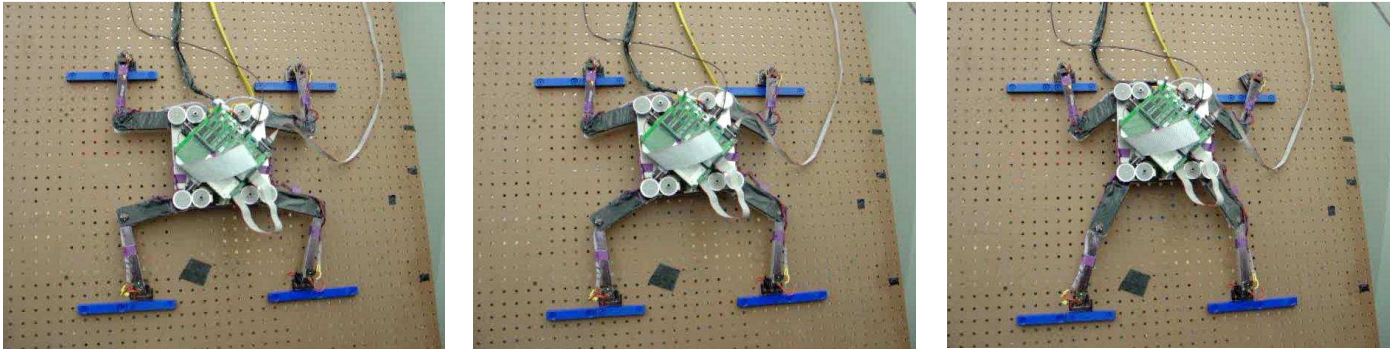


Figure 2. An early version of Tenzing standing-up using force feedback. The body is moved up by extending the legs while maintaining force on the hands, preventing the robot from losing its balance.

inside the $1\frac{1}{2} \times \frac{3}{4}$ inch inner-arm. Whereas this makes precise positional control of the robot more difficult (because of backlash) than if motors were mounted at the joint, it has the benefit of making the limbs compliant and making the limbs effectively massless when compared to the mass of the body. At the end of each 11" long limb is a small 2" wide hand that pivots freely, but is weighted to always face down. A software controlled LED is also mounted at the hand to facilitate the location of the hand by the image processing software.

Instead of incorporating a multi-axis force transducer for each limb the mechanical design was simplified and each appendage has only a pressure sensor in the hand/foot. The pressure sensor uses a Hall Effect sensor to measure the displacement of a magnet mounted on the spring-loaded hand. The sensor can measure contact pressure but cannot detect lateral/tangential forces, and therefore does not provide sufficient information to the control software to keep hands from slipping of the sides of handholds. Instead we must use computer vision to detect whether the hands stay centered on the handholds when the robot changes pressure on a handhold.

The area within which a limb can reach a handhold is limited by the mechanical limits on the rotation of the two limb joints and self-collision. Because the robot is planar and robot's limbs have only two degrees of freedom, limbs cannot cross.

Embedded Controller Design

The embedded controller for the robot is an 8-bit HC12 microcontroller board purchased from Axiom Manufacturing. The controller was programmed entirely in C using a GNU toolchain. An eight bit controller was selected instead of more advanced 32-bit controller running Linux so a hard-real-time force feedback loop could be implemented.

The controller communicated to a personal computer using a dedicated serial port and a simple NACK/ACK-based messaging protocol. The eight motors are controlled using a dedicated pulse width modulation module, with the maximum motor slew rate limited in software.

Grasping Handholds using Force Feedback

Every 3 milliseconds the analog-to-digital converter module samples the four pressure sensors, enabling a responsive pressure feedback of the limbs. This allows Tenzing to stand-up while maintaining all four limbs on their respective handholds. An example of this motion is seen in Figure 2.

Server Design

A server written in Java and running on a standard desktop PC performs all the image processing and high level planning necessary for the robot to autonomously climb to the top of the climbing wall.

Image processing is used to find and locate all the handholds on the wall, the robot's body, hands and feet. Handholds are colored bright blue so to contrast with the brown wall and the robot. As seen in Figure 4 image processing accurately locates all the visible handholds in an image of the wall. The robot body is located using a larger red rectangle centered on the body.

The location of the hands and feet is simplified by using green LEDs to mark their location. The LEDs appear as bright point sources when the image brightness is reduced. Given the location of the hands and body, and the dimension of the robot the server uniquely determines the stance of the robot. Figure 4 shows the real image and the stick figure superimposition.

Once the robot and the handholds are located on the climbing wall, visual servoing is used to guide hands and feet to the next handhold. When the embedded controller on the robot senses that contact is made with the pressure sensor, motion is stopped and the server notified.

Planning a Climbing Route

Finding a good or optimal climbing route up a wall is a different problem than those usually solved in the planning literature. Instead of avoiding collisions, our planner must find a connected path between stable stances. The search space for stable stances is constrained by the finite set of handholds available to the climber. However, the overall approach is still the same as for a PRM planner. We must first find the stable stances for the climber on the wall, equivalent to finding collision-free robot positions. Then we must use a local planner to connect these stances, and finally search for a path that links a set of stances from the bottom to the top of the wall.

Stable Stances

The local planner must find all quadruples of handholds that allow the robot to establish a stance. Some stances allow the body a large range of motions while maintaining stability and contact with the handholds. A climbing route can be considered easy if the robot then moves between stances that give the robot the most flexibility in how it can move be-

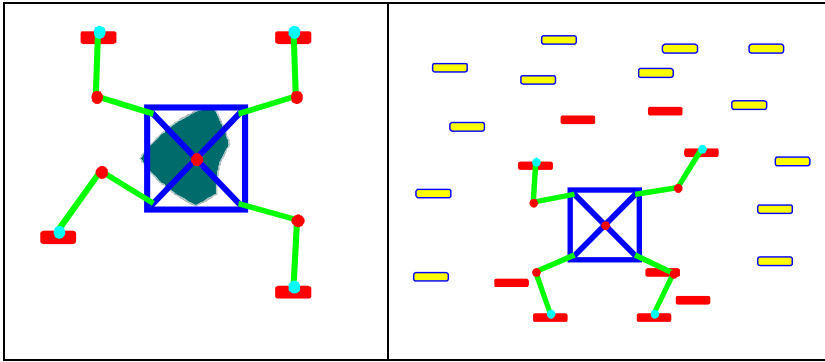


Figure 3. (a) Given the closed chain made by connecting the four handholds, the area which the robot can move the center of the body is constrained to the green area. In this configuration of holds this entire area provides stable stances. (b) The reachable hand holds for the given stance are shown in red.

tween successive stances.

Since feasible robot stances are constrained by the relative location of the handholds, using a PRM approach that randomly generates stances is not efficient since most of these stances will be infeasible. Instead our local planner searches the set of known handholds for sets of four handholds that allow a feasible stance for the robot and then determines the region of stability for that stance. Additionally, the mechanical limits imposed by self-collision of the robot limbs means that for any set of four handholds, there exists only one unique mapping between the limbs to a set of four holds, given the additional constraint that the robot shall remain near vertical and with the head up.

Our planner application, as shown in Figure 3, marks the feasible location of the center of the robot body as a green region. Because of the placement of the handholds more than shoulder width apart the set of stable stances coincides with the set of feasible stances.

Currently, all our handholds are identical so we do not consider bias in the quality of each stance by the relative goodness of each handhold. Also, Tenzing is strong enough

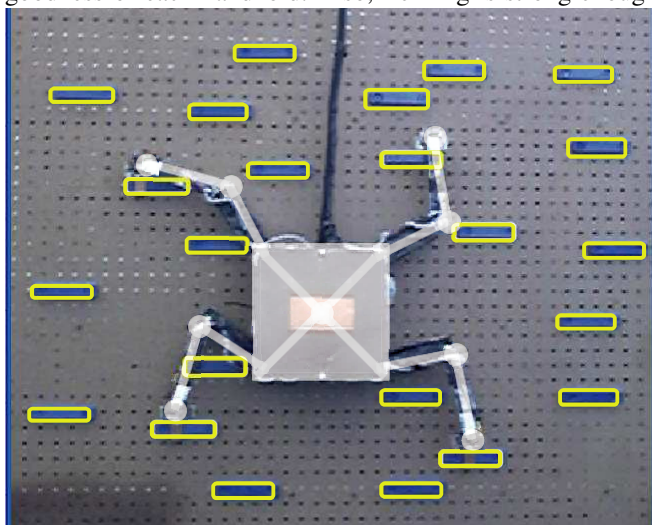


Figure 4. The robot and handholds are marked after being detected by image processing. The algorithm use motor angles only to help determine if the elbows are orient up or down.

so that it can always maintain a stable stance even when one limb is removed from a handhold, using force feedback on the remaining three handholds to maintain its stance. With other mechanical designs or humans, this is not true on harder climbs.

Local Planner

How a climber moves from one stance to the next stance is determined by the relative position of the handholds and the “goodness” of each handhold. In order to perform a quasi-static movement between two stances the stances must have overlapping stability regions, and the robot must maintain stability using three holds while moving the fourth. If these regions do not overlap, dynamic movement would be necessary, so that the climber can use momentum to transition from one stable stance to another [12]. These dynamic techniques are usually

only required by humans on harder climbs. Currently our local planner is very conservative and plans routes that should require no dynamic motions, making sure the robot transitions between two stability regions only where they overlap.

A more sophisticated approach to local planning allows for patterns in the climbing movement. These patterns are similar to the gait that was designed for the climbing robots that used suction cups and magnets. However, because Tenzing must use irregularly placed handholds, a simple gait will not be sufficient to climb from handhold to handhold. With a repertoire of climbing patterns, the local planner can chunk several moves together.

Currently, Tenzing has only one climbing pattern. This pattern, shown pictorially in Figure 5, is a conservative pattern used by most beginning climbers. When at a stable stance, the climber moves to the next independent stance by first moving the legs up to higher foot holds, then moving the torso up by straightening the legs. Now that the torso is higher a new set of handholds can be reached. When using this pattern, the body is only moved when all four limbs are on holds. Future research will be done to allow Tenzing to learn other patterns that work well.

Global Planner

Our global planner searches for a path using A^* that connects a sequence of stable stances from the bottom to the top of the climbing wall. In its simplest form, we maximize the connectivity of the chain of stances in the route, ensuring that any errors in the map or mechanical limitations of the robot, are compensated for by staying in the center of a relatively large stable stance. The cost function can be designed to minimize the maximum risk of falling, minimize the average risk, etc.

Results

We have collected results from our construction of Tenzing and documented Tenzing’s climbing ability at the following URL: <http://www.cs.dartmouth.edu/~spl/Academic/ClimbingRobot/Tenzing/> or Google the following terms to find the site: climbing robot Tenzing.

Our preliminary results show that by using computer

vision the robot can reliably locate itself on the wall and guide its limbs to handholds even with up to 10 degrees of backlash on the belt driven knee and elbow joints. Computer vision is able to reliably extract a map of the handholds and our planner plans a route up the wall that takes into account the rotational limits of the robot's joints.

Conclusion

Our work shows that by integrating computer vision with a robot of simple mechanical design with simple force feedback, a robot can autonomously locate, plan and execute a climbing route up a near vertical climbing wall with randomly placed handholds. By using good sensing and reflexes the robot is able to compensate for many of the mechanical shortcomings of the design.

Future work will include constructing a more flexible robot, including multiaxis force transducers, relax simplifying constraints and add new capabilities. Constraints that we will eliminate include the limitation that the robot body must stay near vertical at all times. As with human climbers, the ability to allow the body to pivot increases the reach and the range of motion of the limbs. We will also relax the constraints on the orientation of the handholds. Whereas currently we only pull down on handholds, we will in the future allow the robot to climb by pulling and pushing sideways on vertical handholds.

Future research will integrate a camera on the robot. The panoramic camera will then only be used to allow the robot to plan an initial path up the wall. All subsequent planning will be done using only the robot mounted camera. The robot will then need the capability to reverse climbing moves, when a dead end is reached.

Additionally students will develop the capability to coach the robot up the wall using spoken commands. A coach will use phrases such as: "the high hand hold", "move your left leg", "move right", etc. This coaching will augment the path planning module.

Acknowledgement

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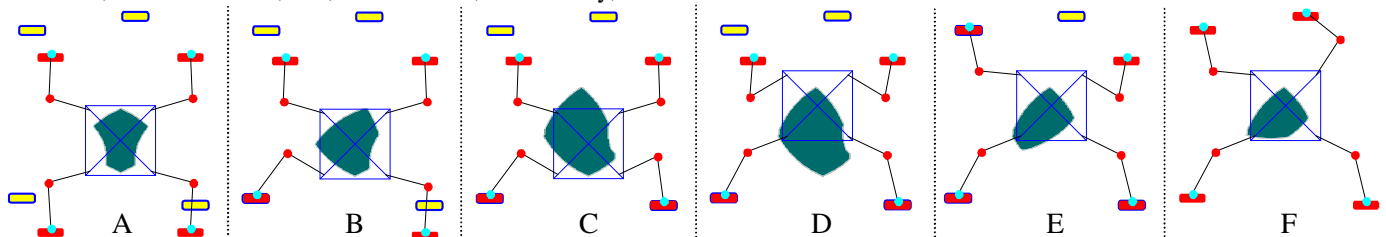


Figure 5. A simulation of the robot climbing from a stance, filled rectangles, to a completely independent second stance, unfilled rectangles, moving one hand at a time. During transition from (c) to (d) the robot only moves its torso. The green region in the center is the reachable extent of the center of the robot torso given the physical constraints.

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