Robust Autonomous Stair Climbing by a Tracked Robot Using Accelerometer Sensors

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One interesting problem that urban search and rescue (USAR) robots face is the process of climbing stairs. In this paper, an algorithm for the autonomous stair climbing is presented, using only pitch and roll angles, as measured by an accelerometer sensor. A skilled human operator is required to climb stairs manually, therefore, doing so autonomously allows for a more efficient robot operation in search and rescue scenarios. Tests were made using RAPOSA, a tracked wheels USAR robot, and results have shown that the proposed control algorithm was capable of climbing several kinds of stairs. An empirical evaluation comparing it with human teleoperation showed an overall more reliable and faster operation in the majority of the tests. This difference is even more significant when the human operator is limited to the robot's eyes.

Keywords: Field Robots; Autonomous Stair Climbing; Motion Control.

1. Introduction

Mobile robots are an active area in USAR, which has been subject to a broad research.[1] Most of this research is motivated by more reliable, faster, safer, and autonomous robots. In a disaster scenario, lifts are not an option, so stairs are the most common way of maneuvering throughout a multi-level building. Robots operating in these scenarios need then to be able to climb stairs. Hence, if robots are capable of doing so in a fast and secure way, the situation awareness capabilities increase dramatically. Moreover, the teleoperation of SAR robots is prone to error when manually climbing stairs.[2] One of the reasons to increase the level of autonomy in USAR robots

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is to permit any person to operate it, even in the absence of experience. Otherwise, operators require extensive training and experience, so that no time is wasted during field operation. This is even more important in the case of stair climbing by the robot.

In this paper a procedure for climbing stairs autonomously is presented. The target robot platform for the present work is RAPOSA,[3,4] displayed in Fig. 1, a teleoperated USAR tracked robot formed by a main body and a frontal body, referred here as arm. The arm angular position is movable. RAPOSA can climb stairs with 45 degrees inclinations. Its weight is distributed in a way that the center of mass is located on its front, which reduces the probability of falling upside down when climbing stairs or obstacles. One dual-axis accelerometer, located in the main body, is used to measure pitch and roll angles of the robot, thus allowing the operator to be fully aware of the robot attitude.

The paper organization is the following: section II as a summary of the related work, section III covers the issue of climbing stairs and the proposed solution, experimental results are presented and discussed in Section V, and section VI presents some conclusions and future work.

2. RELATED WORK

Tracked robots have been identified as particularly useful to overcome difficult surfaces, such as large obstacles and loose soil.[5] This capability reveals itself crucial in USAR scenarios where, for instance, stairs and holes are commonly found.[2] Related works where the used robots have a similar structure as RAPOSA were examined. All of them present an autonomous climbing stairs algorithm that involves video cameras,[6] lasers[7] or sonars.[8] All of these sensors involve costs, mass, volume and energy, and increases the algorithm complexity.

A Kalman filter is used for quaternion-based attitude estimation, fusing rotational velocity measurements from a 3-axial gyroscope, and measurements of the stair edges acquired with an on-board camera[6] or a laser scanner.[7] These methods require accurate camera or laser measurements, which may not be available in SAR scenarios (e.g., deficient illumination). Moreover, the Kalman filter assumes Gaussian noise, and may require fine tuning of the noise model parameters. In contrast, this paper presents a simple algorithm for climbing stairs using only the measurements of one accelerometer. Moreover, a robust behavior is achieved by continuously monitoring the attitude angles in order to prevent the robot from dramatically failing the task by, for instance, falling on its back.

3. CLIMBING STAIRS

The procedure to climb stairs autonomously that is proposed here can be divided in two stages. The first consists on the approach of the robot to the first step using vision for a correct initial alignment. While in the second, the robot climbs the remaining steps using only the accelerometer data.

3.1. *First stage: approaching the stairs*

In this stage vision is used for a correct initial alignment. The contours of the stairs are detected using the Canny edge detection method.[9] Assuming that stairs always present several parallel straight contour lines, their identification is made using the Hough Transform for straight lines detection.[10] From the lines detected, the one that minimizes the midpoint along the vertical axis is chosen. The angle that this line makes with the horizontal axis is then used to turn the robot to become aligned with the stairs. With the robot aligned with the stairs, the arm rises to a 25 degrees angle relatively to the main body and the robot starts climbing the first step.

3.2. *Second stage: stair climbing*

An appropriate positioning of the frontal arm is crucial to maintaining the center of mass sufficient ahead to prevent the robot from falling back. The solution adopted consists in using only the information of the pitch and roll filtered angles as measured by the accelerometers. The variables used to control the robot movement are the velocity (cms^{-1}) of left and right wheels, v_l and v_r, and the angle increment ($^\circ$) that is sent to the motor controller of the arm σ_a. These three variables form an actuation vector $r = (v_l, v_r, \sigma_a)^T$.

The feedback control law used to compute the actuation r is given by

$$r = Cd + \begin{bmatrix} \epsilon \\ \epsilon \\ 0 \end{bmatrix} \qquad C = \begin{bmatrix} c_{11} & c_{12} & c_{13} \\ c_{21} & c_{22} & c_{23} \\ c_{31} & c_{32} & c_{33} \end{bmatrix} = \begin{bmatrix} -\eta & -\mu & 0 \\ -\eta & \mu & 0 \\ -\delta & 0 & -\nu \end{bmatrix} \tag{1}$$

where C is the gain matrix, d contains the current sensor readings of pitch (ϕ_p), roll (ϕ_r) and arm angle (ϕ_a), $d = (\phi_p, \phi_r, \phi_a)^T$, and ϵ is a constant bias speed.

The vector d is identically zero when the robot is on a horizontal ground, with the arm aligned in the direction of the body. The angles in d are oriented as follows: ϕ_p is positive when the robot front rises over the center of mass, ϕ_r is positive when it rolls to the right, and ϕ_a is positive when it is raised up. Because small values of pitch can be ignored, a deadzone is applied to it, so that $\phi_p = 0$ if the pitch angle is lower than 20 degrees. The noisy nature of the roll angle has leaded us to also apply a deadzone: $\phi_r = 0$ if the roll angle is lower than 5 degrees in absolute value. The gain matrix C is constructed using these principles:

- Pitch angle controls the robot movement in common mode, $c_{11} = c_{21} = -\eta$, so that the robot moves slower as the pitch gets higher.
- Roll controls the robot movement in differential mode. This means that the respective coefficients should be symmetrical, $c_{22} = -c_{12} = \mu$.
- The arm is controlled in position with a proportional gain ν, where its reference position is $-\frac{\delta}{\nu}\phi_p$, according to (1). This allows the arm to be lowered as the pitch increases, thus maintaining the center of mass as ahead as possible.

The constant bias vector ϵ provides a constant base speed of the wheels in the absence of large pitch and/or roll values.

After extensive testing of climbing stairs while teleoperating the robot, it was realized that the best way to climb stairs is with the arm slightly lowered (approximately -5 degrees). This can be understood, since having the arm in this position, the center of mass will be located ahead, as well as being better for the tracked wheels to take hold off the next stair step. This was found to be valid for stairs with an inclination lower than about 30 degrees.

One of the major problems with stairs with high slopes is that, even with the arm down, depending on the pitch value, moving forward may lead the robot to fall upside down. In order to fall towards the next step, the center of mass must be ahead of the contact point at the fore. In order to prevent this from happening, and thus provide the robot with a robust behavior, three exception states were introduced (S1–S3). The first one (S1) is reached when the pitch is higher than a threshold T_1 (35 degrees in the tests). In this case, the robot stops until the arm is sufficiently lowered, then it starts moving slowly. If pitch keeps rising until reaching a second threshold T_2 (42 degrees in the tests), the exception state (S2) is triggered, in which the robot starts moving backwards slowly, until leaving this second exception state. If S2 is achieved consecutively in the same step, the algorithm assumes that there is some obstacle blocking the way. Therefore, the robot moves back and asks the robot operator to choose, using the images captured by the robot, the best direction to proceed avoiding the obstacle. In the cases where the arm is lowered significantly, when the robot falls forward to the next step, it will get stuck in the corner formed by the next step. Hence, the robot stops moving (exception state S3), while waiting the arm to return to its nominal angle (aligned with the body). The inclusion of these states makes the robot less dependent on the performance of the feedback controller alone, namely in exceptional situations.

Finally, the robot assumes that the stairs ended when pitch returns to zero (unless previously interrupted by the operator), thus concluding the autonomous stair climbing algorithm.

4. RESULTS AND DISCUSSION

Many tests have been conducted in stairs of diverse dimensions and materials, in order to evaluate the control algorithm. The coefficients of the controller were adjusted based on these tests. The controller parameters used were: $\epsilon = 20cms^{-1}$, $\eta = 0.2cms^{-1}deg^{-1}$, $\mu = 0.5cms^{-1}deg^{-1}$, $\delta = 0.02$, and $\nu = 0.1$.

To evaluate the performance of the algorithm, the robot was placed 5cm from the first step of the stairs. Then the algorithm was launched and the pitch, roll, and arm angles were measured together with the actuation vector r.

Figure 1 shows a sequence of images showing the robot climbing stairs. Figure 2 refers to the sensory data d, where pitch and roll were measured from the accelerometer and the arm angle from the arm potentiometer.

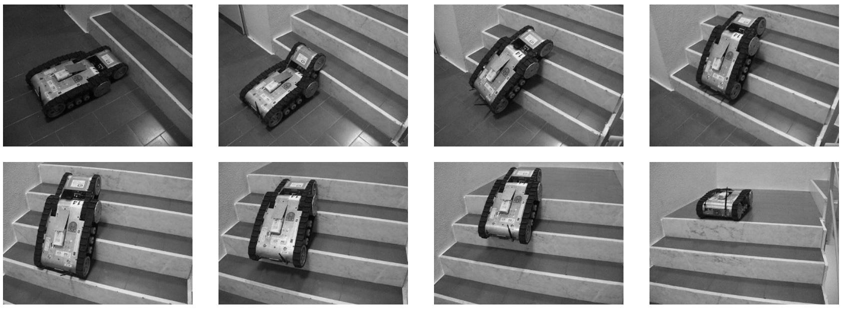
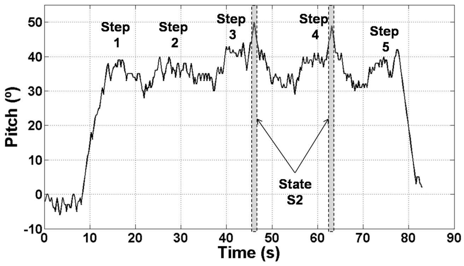
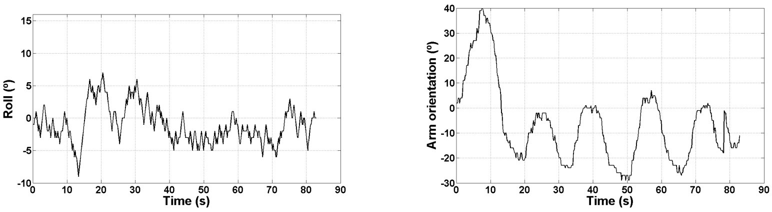


Fig. 1. Sequence of photographs showing RAPOSA climbing stairs

Regarding the pitch plot in Fig. 2, and taking into consideration the inherent noise, five stair steps are visible: the local maximum corresponds to the points where robot presents the higher pitch angles. During the third



(a) pitch



(b) roll

(c) arm

Fig. 2. Sensory data during stairs climbing: pitch, roll and arm angles.

and fourth step, the robot reached the exception state S2, consequently, the robot moves backwards during a small period of time to force the robot to fall forward (thus preventing it from falling backwards).

The roll angle measurement, shown in Fig. 2, displays the misalignment with the stairs vertical, as well as mechanical and electrical noise. Concerning the arm position, the attack angle for the first stair step is the time interval when the arm has positive angle.

Figure 3 shows a test where human intervention disturbed its direction during climb (at about 35 seconds), and its response to it. The significant increase in right wheel velocity was the step taken by the robot to resume alignment with the stairs.

Concerning the vision-based alignment method used to place the robot in the best orientation to start climbing (section 3.1), all performed tests were successful.

An evaluation was conducted to compare the performance in stair climbing of the proposed method against a human operator. For each of the tested stairs, the climbing time was measured in the three possible ways of controlling a mobile robot:[11] "RC-ing", where the operator controls the robot and can view it and its relationship to the environment; Teleoperation, when

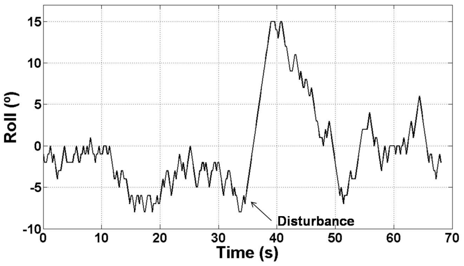


Fig. 3. Roll angle response after human intervention (disturbance).

the operator controls the robot viewing the environment only through the robots eyes; and Autonomous, where the proposed climbing algorithm is executed. Table 1 shows the average time taken, for different types of stairs (wood (1), polished (2) and unpolished (3) marble), and for these three situations, together with the percentage of success. The amount of tests to obtain these results was 10 tests for each case (the 3 modes on the 3 different stairs).

Table 1. Experimental Results.

			Autonomous		Human operated			
					camera view		direct view	
Stairs label	Number of steps	Slope (°)	Time (s)	Success (%)	Time (s)	Success (%)	Time (s)	Success (%)
(1)	10	32	100	100	115	97	90	98
(2)	11	30	130	100	110	100	85	100
(3)	5	36	80	97	95	60	65	95

These tests, made by different persons with different skills operating the robot, showed that usually, the wasted time when people is teleoperating is due to sending of wrong commands to the robot, such as lifting the arm instead of getting it down, or moving to the left instead of to the right. These small errors make the task of climbing stairs much longer and sometimes it may lead to accidents. This explains the higher success rates accomplished by the autonomous mode, as well as the success of proposed approach.

5. CONCLUSIONS AND FUTURE WORK

An algorithm to allow a SAR robot to autonomously climb stairs was presented, along with experimental results obtained in several kinds of stairs.

When compared with a human operator solely using the robot vision cameras, the algorithm proved more reliable, and faster in some of the tested stairs.

Tests made on curved stairs, the algorithm proved to be partially effective, because of the roll angle control mode. For this kind of stairs (including spiral ones), an improvement of this algorithm would be interesting.

The aspects that will be improved are the accelerometer used, since the measured values showed significant noise. Another aspect is the speed of the arm, which moves at a lower constant velocity, and obliges lower wheels speeds than the desirable.

It should be noted the simplicity of the approach presented here, namely when compared with the literature, which nevertheless has shown capable of accomplishing the task. This simplicity contributes to a robust behavior.

References

1. E. Messina and A. Jacoff, Measuring the performance of urban search and rescue robots *IEEE Conference on Technologies for Homeland Security* May 2007.
2. J. Casper and R. Murphy, Workflow study on human-robot interaction in usar *Proceedings IEEE International Conference on Robotics and Automation (ICRA-02)* 2002.
3. C. Marques, J. Cristovão, P. Alvito, P. Lima, J. Frazão, M. I. Ribeiro and R. Ventura, *Industrial Robot: An International Journal* **34**, 332 (2007).
4. C. Marques, J. Cristovão, P. Lima, J. Frazão, M. I. Ribeiro and R. Ventura, Raposa: Semi-autonomous robot for rescue operations, in *Proceedings of IROS2006 — IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2006.
5. F. Hardarson, *Locomotion for difficult terrain*, Tech. Rep. TRITA-MMK-1998:3, Mechatronics Division, Dept. of Machine Design (1997).
6. A. I. Mourikis, N. Trawny, S. I. Roumeliotis, D. M. Helmick, and L. Matthies, *The International Journal of Robotics Research* **26**, 737 (2007).
7. D. Helmick, S. Roumeliotis, M. McHenry and L. Matthies, Multi-sensor, high speed autonomous stair climbing, in *IEEE/RSJ International Conference on Intelligent Robots and System*, 2002.
8. S. Steplight, G. Egnal, S.-H. Jung, D. Walker, C. Taylor and J. Ostrowski, A mode-based sensor fusion approach to robotic stair-climbing, in *2000 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2000.
9. J. Canny, *IEEE Transactions on Pattern Analysis and Machine Intelligence* **8**, 679 (1986).
10. R. O. Duda and P. E. Hart, *Communications of the ACM* **15**, 11 (1972).
11. R. R. Murphy, *Introduction to AI Robotics* (MIT Press, Cambridge, MA, USA, 2000).