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Motion control of an omnidirectional climbing robot based on dead reckoning method

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A B S T R A C T

While omnidirectional wheels enable a holonomic drive and a good maneuverability, the slippage of the wheels as an inherent characteristic of the omnidirectional wheels prevents using rotary shaft encoders as a reliable source of data for the robot's odometry. When installed on a climbing robot, omnidirectional wheels may suffer from additional slippage on the surface. In a previous study, we described how the resulting vibration decreases the trajectory following accuracy of the robot, and why rotary encoders, as the most popular dead reckoning method cannot be used. In this paper, we address this problem by integration of low cost and light weight exteroceptive sensors, i.e. an accelerometer and an optical flow sensor. The Omniclimber climbing robot was used as the testing platform in this study. Omniclimbers are omnidirectional climbing robots that can climb and navigate over flat and curved structures. We attempt to compensate the errors due to the wheel slippage through closing the position control loop without significantly increasing the robot's weight, cost and complexity of the robot. We also integrated an algorithm which corrects the robot kinematics on the curved structures based on the curvature diameter and the robot's heading angle. Taking advantage of these sensors and algorithms we could make remarkable improvements on the path following accuracy of the Omniclimbers, which is presented in this article.

1. Introduction

Climbing robots have received much attention in recent years due to their potential applications in construction, inspection and maintenance of tall structures, such as industrial tanks, reservoirs, buildings, bridges, posts, towers, chimneys, wind turbines, and ship hulls. Climbing robots can be categorized based on their surface adhesion or their locomotion mechanism. For holding a robot attached to a smooth surface, the mainly used systems are: suction cups [1–3], attraction force generated by the propeller (negative pressure) [4,5] or magnets [6–9]. Other new systems such as biological inspired adherence through wet or dry adhesion and electro adherence have also been developed (See [10] for instance). Robots whose end-effectors match engineered features of the environment like fences or porous materials, pipes or bars [11–15] were also developed.

Gas and oil tanks, wind turbines, pipelines and marine vessels are examples of the structures which are targets of this research work. Such structures share three common aspects:

- They need a periodical inspection, maintenance or cleaning.
- Their exterior circumference is flat or convex.
- Most of them are built from ferromagnetic material.

For inspection of such structures we developed Omniclimbers, Omnidirectional climbing robots that can climb from ferromagnetic structures, whether they are flat or curved [16,17]. Taking advantage of the three omnidirectional wheels, placed at 120°, the holonomic drive robot can move in any direction on vertical surfaces without requiring to change its yaw angle. Its flexible chassis allows it to adapt to both flat surfaces and tubes up to 220 mm in diameter. Chassis parts and wheels are 3D printed in PA 2200 through selective laser sintering. The robot is untethered possessing all controllers and batteries on-board and a wireless communication module through Bluetooth. Table 1 and Fig. 1 show the main characteristics of the last version of the robot. More detailed information about the mechanical design of the robot can be found out in [16].

In spite of several developments in the area of climbing robots, the localization, navigation and motion control systems of these robots are still open problems. The reason is that the climbing and adhesion mechanisms still present a challenge in many

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Table 1
Omni-climber VI technical specs.

Dimensions	
Diameter × height	197 × 84 mm
Mass	1110 g
Actuation	3 MX-64 rotary actuators
Battery	On-board LiPo 1000 mA h
Adhesion force*	
Switchable magnet off	25.5 N
Switchable magnet on	45 N
Wheels	70 mm diam. magnetic omni-directional wheels
Performance	
Max climbing speed	14 cm/s
Min radius of structure	110 mm
Payload*	1200 g
Movement	Fully omni-directional

* Measured on 1 mm thick sheet of steel.

aspects. A few research works reported prototypes with sensor integration and pose correction, but yet the results were poorly reported. As an example of this is the work of I-Ming Chen et al. which developed a two-dimensional walking-climbing robot using a gait generation mechanism but without any sensors to perform real-time corrections to the navigation [18]. Oswaldo et al. reported application of accelerometers in a hot melt adhesive climbing robot [19]. However the control architecture was not described and results of the navigation accuracy were not reported. Tavakoli et al. used an inertial module in order to correct the positioning errors of the step by step based climbing robot, 3DClimber [20,21]. They used a combination of a range sensor and an inertial unit to compensate the positioning error of the climbing arm. In another effort, the same group addressed the 3DClimber localization and mapping with a mobile external observer. They used a terrestrial robot equipped with a Microsoft Kinect unit in order to localize the climber which is equipped with several visual tags [22]. Longo et al. also used an inclinometer for the step-by-step based climbing robot Alicia [23], but they also did not provide information about the navigation accuracy of the robot. In the category of wheel based climbing robots, Tache et. al. presented Three-Dimensional Localization for the MagneBike Inspection Robot relying on a 3D point cloud of the climbing structure by integrating a laser scanner on the robot [24] which was later used for surface reconstruction and path planning with the Magnebike robot [25].

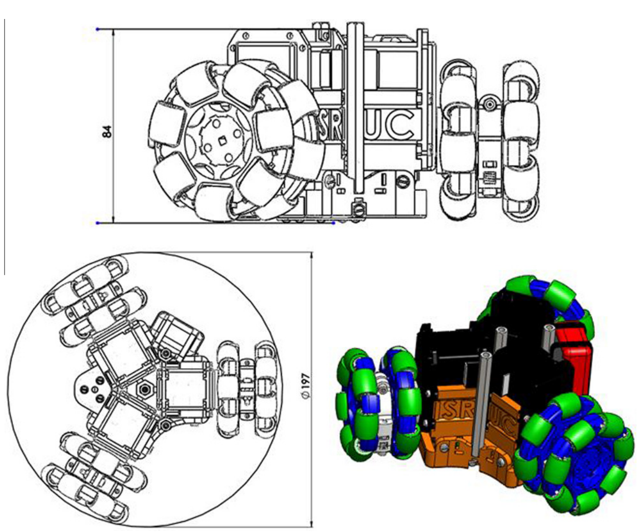

Fig. 1. OmniClimber-VI.

Omniclimber robots are wheeled based robots that proved to have the following characteristics:

- They adapt very well to flat and curved ferromagnetic surfaces with minimum diameter of 220 mm.
- Thanks to their omnidirectional wheels, they have good maneuverability, they can move in any direction on the vertical surface without turning the chassis (or changing their yaw angle).

Yet the last version of the Omniclimber had the following problems:

- When operated on curved surfaces the omnidirectional robot kinematics changes.
- Discontinuous nature of the omnidirectional wheels causes vibration on the chassis [26]. Due to lack of exteroceptive sensing units, the robot could not follow a straight path precisely.

In this research work we attempt to address the path-following problem of the Omniclimber, in which the vehicle is required to converge to and follow a path, without a specific temporal specification. That is, we try to compensate the errors due to the wheels slippage through closing the position control loop with exteroceptive sensors. Considering the limited weight that Omniclimbers can lift, this tasks should be done without significantly increasing the robot's weight and complexity. Utilization of rotary shaft encoders as most popular dead-reckoning method in mobile robotics, is not an appropriate choice for omnidirectional robots due to the slippage of the wheels [27]. Wheel slippage is also a well-known problem on climbing robots. Being an omnidirectional climbing robot, Omniclimber cannot take advantage of wheel encoders as a motion feedback and thus other methods should be considered. For this purpose we integrated a position control loop and motion planning algorithms that rely on two low cost and light weight sensors: A three axis accelerometer; and an optical flow sensor.

The general kinematics of omnidirectional robots has already been solved for flat surfaces [28]. However, for curved surfaces this kinematics is not valid and should be corrected. In this research work we first developed the new kinematics model of the Omniclimbers on the curved structures. This kinematics model can be used for robots with 3 omnidirectional wheels that should navigate on curved structures. We then developed a kinematics correction algorithm which corrects the wheels velocity based on the following 2 inputs: The surface curvature and the robot's actual orientation on the curved structure. While in this study the surface curvature is considered constant (as this is usually the case in reservoirs and pipes), the second parameter, the robot orientation, neither is constant nor can be estimated by relying on the wheels odometry, due to the wheel slippage. Thereby we used the integrated 3 axis accelerometer and an orientation estimation algorithm which after filtering the vibration and acceleration components of the output, estimates the orientation of the robot and feeds it into the kinematics correction module in order to correct the wheels velocity for a more precise path following. Moreover, by integrating the optical flow sensor that measures the distance paved by the robot, and fusing the data with the estimated yaw angle of the robot, we could estimate the robot's position and compensate the wheel slippage. We performed several tests on vertical structures and compared the results.

2. Kinematics of the Omniclimber robot on curved surfaces

The kinematics of a 3 wheeled omnidirectional platform can be derived from the projections of each of the wheels velocity components on the reference axis of the robot (Fig. 2). When moving on a