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A NOVEL HOLONOMIC MOBILE MANIPULATOR ROBOT FOR CONSTRUCTION SITES

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This article describes a mobile manipulator robot designed to work at height on construction sites. The robot comprises a mobile platform and a scissor lifter on which an ABB 6 DoF manipulator is mounted. The mobile base is characterised by holonomic kinematics, provided by a novel designed omnidirectional wheel system that can travel directly and autonomously to desired poses. The robot was successfully tested in a construction site scenario to perform drilling tasks.

Keywords: Construction site; Mobile manipulation; Holonomic; omni-wheel; ROS.

1. Introduction

Construction work involves a variety of challenging and hazardous scenarios which cannot be easily automated. The main issues that need to be addressed are the dynamic and relatively unstructured environment and the complexity of the tasks that need to be carried out. Hence, the industry has traditionally relied heavily on manual processes and has not made major productivity gains found in other sectors; in addition, it is suffering from widespread labour shortages.

Given these issues, efforts are being made to introduce innovations such as automation and robotics to improve worker safety and increase productivity levels in line with other domains, as it is well known that robotics and automated systems have the potential to revolutionise the field. In many applications, robots are more efficient and able to be more precise than humans and can perform dangerous and physically demanding tasks, thereby reducing the risk to workers and allowing them to focus on more cognitive tasks. As robotics continues to advance, construction firms are becoming more receptive to adopting automated processes. Many diverse applications within the industry can be enhanced using robotic technology, e.g. traditional activities such as welding, cutting, material handling, and drilling.

Variations of robotic construction platforms have been developed since the 1970s, with on-site operations beginning in the 1980s.[1] The specialisation of construction robots in bricklaying, welding, demolition, and surveying sectors have been advanced, due to the repetitive and monotonous nature of the work. Anlinker et al.,[2] Lehtinen et al.,[3] and Slocum et al.[4] developed some of the earliest bricklaying and welding robots, utilising robotic grippers on a moveable platform. Dharmawan[5] outlines the development of an industrial robotic arm mountable on scaffold structures (used for in situ large-scale construction), highlighting the need to reach elevated heights on construction sites. Since 2012, nLink from Norway[6] has been developing a mobile scissor lifter fitted with a robotic arm, providing on-site assistance for overhead drilling with autonomous control. However, until recently, manufacturing and assembly robots have been confined to the regulated workcells in industrial environments. With the advent of innovative localisation and detection systems, other types of service robots have recently been emerging because they can operate safely and more readily in wider rugged environments such as construction sites.[5,7]

Precise control of construction robots is vital in compliance with safety regulations to ensure safety and effectiveness, especially as there are many possible hazards present on building sites. Efficient collision-free path planning is particularly important and has been explored in[8] to achieve obstacle avoidance in an unknown environment with static and dynamic obstacles. Different levels of autonomy have also been explored for construction robots, mainly fully autonomous robots and teleoperated robots.

The objective of this paper is to introduce a mobile robot that was developed to carry out a variety of tasks in construction sites. The remainder of the paper is structured as follows. Section 2 describes the methodology used to select the robot's kinematics and Section 3 presents details of the robot developed in a systematic manner starting from system design, mechanical design, and ending with software and control. Section 4 presents results of experiments carried out to test the robot, and section 5 presents conclusions from the research.

2. Methodology of selecting robot's kinematics

The most important part of work was to select a kinematic configuration of a robot that can provide high manoeuvrability, good obstacle crossing capabilities, good stability during all operations and high positional accuracy while being relatively easy to develop and manufacture. The main purpose of the mobile platform is to carry the robotic arm while it performs manipulation tasks. Thus, the platform must have good stability when stationary otherwise extrinsic motion errors may be introduced in the robotic arm system, affecting the accuracy of the arm's end effector position. The platform must also have precise and stable control to enable the above criteria to be met.

The desired manner of motion determines the type of drivetrain system used for the mobile platform. Typical drivetrain configurations include Ackermann steering, differential drives, and omnidirectional drives. Ackermann steering is the least manoeuvrable of the three as the turning circle is large, and zero radius turns cannot be accomplished. Differential drive is more manoeuvrable, although estimating the orientation is more difficult. It also requires greater power, and is difficult to find tyres that can withstand differential drive turning for a long time. Swedish or Mecanum wheels have greater manoeuvrability and do not require high power to turn, although these types of wheel require a clean surface to operate.

To further investigate the possible drive systems, two small pre-prototype robots were designed and developed. One was designed with an omni wheel configuration using four Swedish wheels connected to individual drive motors. The second was built using four classic wheels, each with its own drive and steering motor stack, in an omni-steering arrangement. Both robots were developed with similar control architectures. Through experimentation and trials of the two systems, which included control accuracy tests on uneven terrain, it was found that the omni-steering was the optimal design for our application.

3. Mobile platform

The developed mobile platform is a semi-autonomous scissor lifter with four novel omni-wheels. The maximum height of the scissor lifter is 2 metres. The lifting mechanism is a hydraulic cylinder what can lift payloads of up to 150 kg. The driving system consists of four omnidirectional wheels, where each wheel is powered by two actuators: the first is responsible for yaw motion (turning), and the second is responsible for normal rolling to drive the robot. The second wheel, which is responsible for moving the robot, is attached to a passive suspension system. The omni-wheel is controlled by a custom lower-level controller that regulates desired roll speed and yaw actuator position. The mobile platform is also equipped with a mobile

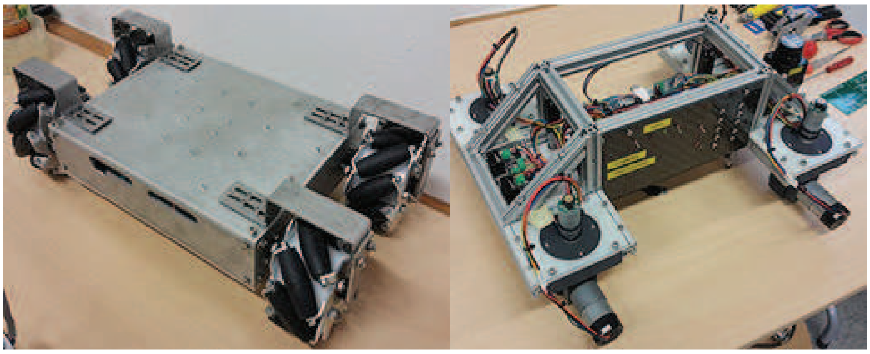


Fig. 1. The pre-prototypes developed to compare properties of kinematic configuration. *Left* - a robot with Swedish wheels, *Right* - a robot with omnidirectional wheels.

camera, allowing visual observation on an external computer. The main controller of the platform runs on Robot Operating System (ROS), which allows easy adaptation and quick development of future components. In the current version, the robot can autonomously travel to the desired pose via a series of waypoints, and stops if obstacles are detected. The platform has been designed to allow easy transportation to various construction sites (the footprint is like a car, and a winch is fitted to the front of the chassis). The parameters of the robot are given in Table 1.

parameter	value
weight	500 kg
max. velocity	1.5 m/s
max. height (platform)	2 m
max. load	150 kg
power	1 kW
max. slope	8 deg

3.1. *Safety*

While there are currently no standards specifically for ”construction robots”, the developed robot would be covered by the following safety and risk assessment standards:

- ISO 10218:2011: Robots and robotic devices – Safety requirements for

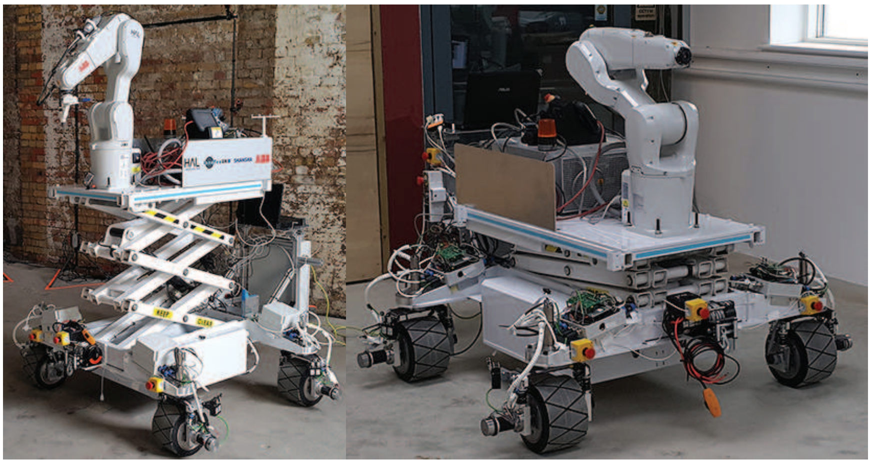


Fig. 2. The final robot developed within the project.

industrial robots (Part 1: Robots[9] & Part 2: Robot systems and integration[10])

- ISO TS 15066:2016: Robots and robotic devices – Collaborative robots[11]
- ISO 13482:2014: Robots and robotic devices – Safety requirements for personal care robots[12]
- ISO 12100:2010 Safety of Machinery – General Principles for design – Risk assessment and risk reduction[13]

To comply with these standards, a number of safety features were implemented at different levels of the robot system:

High-level software

(a) Functional safety-related control — an immediate Emergency STOP command can be sent by E-stops initiated manually to take the robot to a safe state and shut down the system.
(b) Obstacle detection system — the system can identify and avoid obstructions at ground level.
(c) Constant monitoring of robot's inclination — the scissor lifter will automatically retract if the platform is in danger of tipping.

Lower-level hardware

(a) Motor protection — the controllers have over-current, over-voltage and short-circuit protection sub-systems.
(b) Limit switches — safety switches on the wheel stack prevent yaw

motors from exceeding their rotation limits.

Electrical safety-related features

(a) Use of safe voltage — Extra-low voltage (ELV) of 48 VDC and 12 VDC are used (except for the ABB robot arm), which minimises the risk of electric shock.
(b) Isolation of ABB power supply from the mobile platform — power supplies are separated in accordance with separated extra-low voltage (SELV) describe in IEE Wiring Regulation BS 7671.[14]
(c) 4 Emergency STOP buttons around the robot — in the event of software failure, relays can physically cut power to the motors.
(d) 1 Emergency STOP button tethered to robot — a button that is not fixed to the chassis can be activated at a distance from the robot platform.
(e) Toggle power switch
(f) Optimally selected motor torque

Mechanical safety-related features

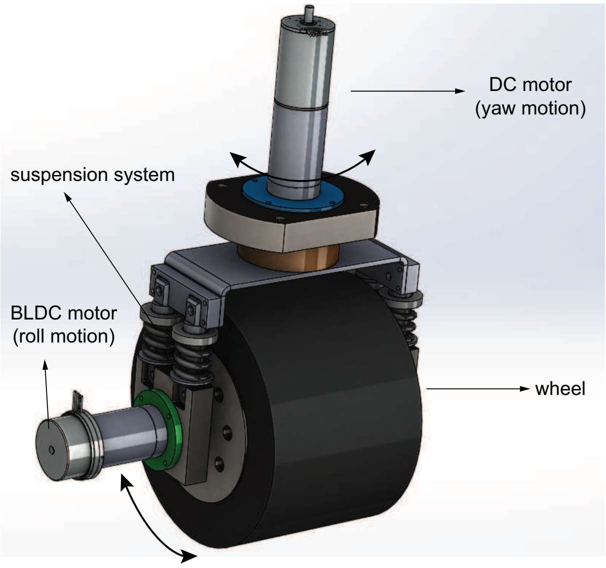
(a) Minimal number of sharp corners, pinching, crushing point, etc
(b) Partially enclosed rotating and hydraulic equipment
(c) Intrinsically stable static design.

3.2. *Mechanical design*

The base of the robot is built around a scissor lifter to which four omni-wheels are attached. The key element of the design is an omni-wheel that allows the robot to travel in any direction without re-orienting the robot chassis. The base of the wheel stack consists of a fork element that holds a driving wheel. The wheel is actuated from the side by a BLDC motor, while a DC motor rotates the fork element. The fork is supported by two bearings that can support axial and radial loads. The whole stack must withstand high stresses due to the considerable mass of the overall robot (550 kg); hence, stress and fatigue analysis was an important element of the design process.

3.3. *Hardware architecture*

The omni-wheel motors are directly controlled by Maxon Motor's controllers, which amplify the signal from embedded computers using a custom-developed control framework. Each omni-wheel's computer regulates the yaw position and roll speed. This sort of structure is compatible with a



sample stress analysis on a fork element:

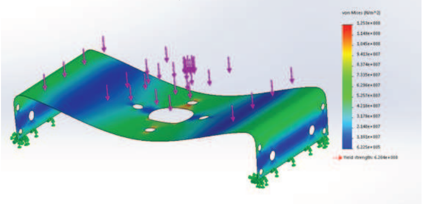


Fig. 3. The omni-directional wheel - the key element of the CAMERA robot

standard kinematics model of a mobile robot; thus, it was easy to implement the kinematic-based controller. That omni-wheel computer communicates with the main controller (laptop with ROS installed) via the UART protocol.

3.4. *Software and control*

The software architecture for the robot is based on ROS[15] as middleware, installed on a computer running Linux. The majority of code is developed using Python except for critical performance parts, where C++ is used. The JSON-ROS bridge server is developed at the top of the architecture to accept requests from a server that controls a high-level construction site scenario. The JSON server translates the incoming strings to ROS service requests and topic data, and converts ROS service responses to JSON string

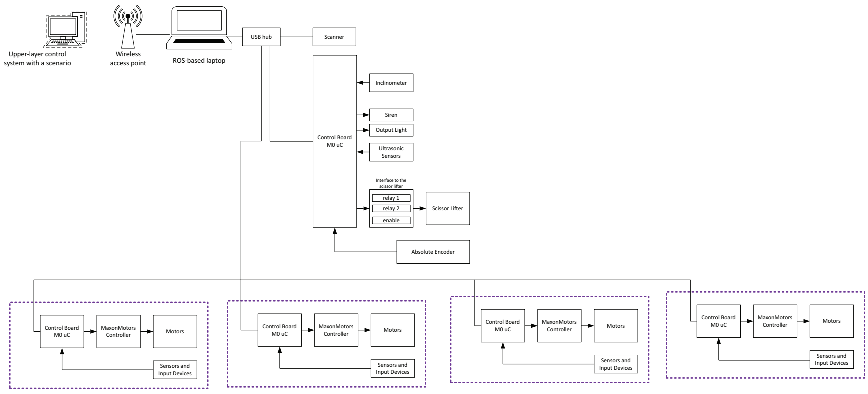


Fig. 4. The general overview of a system design

feedback and sends this back to the scenario server. The heart of the system is the autonomous controller module which processes localisation and obstacle avoidance data and publishes motion commands to drive each wheel individually. In the current version of the robot, the pose of the robot is estimated by using on-board encoders-based odometry; alternatively, the robot can be localised by using an OptiTrack system. The developed controller can drive the robot via the desired path by using an architecture presented in Fig. 5. On the lower level, there are speed controllers for driving wheels, and position controllers for the yaw actuators that regulate desired speed and position respectively.

For the low-level control, two custom hardware interface modules were developed to communicate with the omni-wheels via serial connections.

4. Experiments

The developed mobile platform allows for controlling the robot by using a variety of kinematic strategies; three strategies have been explored; namely, Ackermann steering, modified Ackermann steering in which the rear wheels rotate in the opposite direction to the front wheels, and holonomic motion that exploits omni wheel motion features. In the first series of experiments, the robot was moved to a specific pose with the selected kinematics. During the experiments the pose of the robot was estimated only based on encoder odometry; thus, the positional accuracy in the tested system depended on many factors, such as the path travelled, obstacles, and wheel slip. When moving in a square of approximate area 10x10 metres, the platform was able to position itself with an approximate accuracy of 30 cm, which was

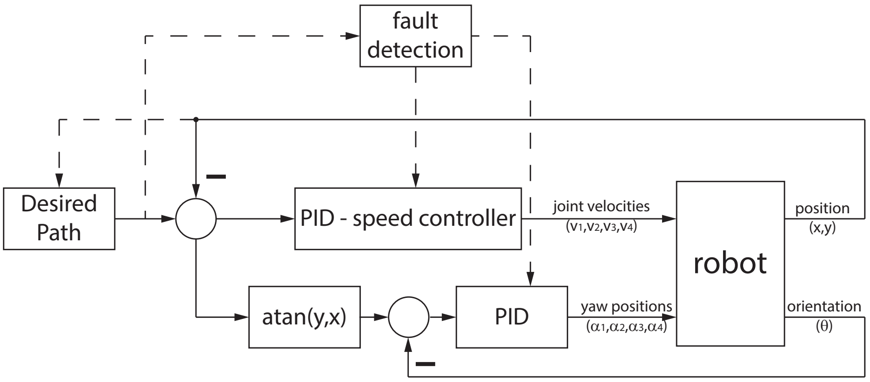


Fig. 5. The control architecture of the global position controller of the robot

sufficient for a mobile manipulator base to reach the desired drilling locations so that the on-board manipulator can carry out the drilling task to the desired level of accuracy.

In the final series of experiments, a scenario was tested where the robot task was to drill at precise locations in a construction site environment. The scenario involved mobile robot platform navigation to the required location, raising the scissor lifter to ensure the point of interest is within the workspace of the robot arm, and finally utilising arm movement control and evaluate the performance of drilling tasks. To drill precisely, the ABB manipulator was localised with an OptiTrack camera system. This allowed successful task completion.

5. Conclusions

This paper describes the development of a novel mobile platform for use in the construction industry to perform mobile manipulation at height. The robot can move autonomously to a specific pose by exploiting three different kinematics. The omni-wheel design has permitted satisfactory improvements in robot manoeuvrability, stability, and ability to overcome obstacles when compared to pre-existing similar robots. The platform can be used for a variety of novel applications within the industrial construction site and beyond.

6. Acknowledgements

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