Abstract—The development of mobile robot platforms for inspection has gained traction in recent years. However, conventional mobile robots are unable to address the challenge of operating in extreme environments where the robot is required to traverse narrow gaps in highly cluttered areas with restricted access, typically through narrow ports. This article presents MIRRAX, a robot designed to meet these challenges by way of its reconfigurable capability. Controllers for the robot are detailed, along with an analysis on the controllability of the robot given the use of mecanum wheels in a variable configuration. Characterization on the robot’s performance identified suitable configurations for operating in narrow environments. The experimental validation of the robot’s controllability shows good agreement with the theoretical analysis and the capability to address the challenges of accessing entry ports as small as 150-mm diameter, as well as navigating through cluttered environments. This article also presents results from a deployment in a Magnox facility at the Sellafield nuclear site in the U.K.—the first robot to ever do so, for remote inspection and mapping.

Index Terms—Design, extreme environment, mechatronic, reconfigurable.

I. INTRODUCTION

The need for inspection, maintenance, and repair in extreme environments has grown considerably following the Fukushima incident and the continued aging of nuclear facilities [1]. These tasks are nontrivial, requiring substantial cost, and where human operators are involved, there is an element of risk to their health when working in these environments. Faced with these challenges, the use of mobile robots has gained interest as risks to human health can be mitigated and robots can, in some cases, perform tasks that humans are unable to [2]. Even so, challenges remain in deploying and operating mobile robots in these environments. One such challenge is navigating through constrained and cluttered areas, and another is that access points may be restricted, for example, many areas in legacy nuclear facilities can only be accessed through a 150-mm access port [3].

Reconfigurable terrestrial robots with movable joints offer a solution to these challenges. A typical robot setup would comprise two or more rigid bodies that are connected by movable joints, with locomotion provided by wheels or tracks. The range of configurations allow such robots to access areas through small ports and to traverse through highly constrained environments such as inside pipes, ducts, or between tightly spaced obstacles. Notable platforms that have been developed for such environments typically employ the use of tracks in their driving mechanisms, due to the significant presence of rubble and loose dirt [3], [4]. However, for semistructured environments, such as legacy nuclear facilities, an alternative driving mechanism can be used since the terrains encountered can be considered more traversable.

To this end, we propose the Miniature Inspection Robot for Restricted Access eXploration (MIRRAX), shown in Fig. 1(a). Sensors mounted on the arm enables 3-D reconstruction [see Fig. 1(b)] or other mission-specific tasks. The design consists of four mecanum wheels, each pair connected to an actuated link, which is, in turn, connected to the base link. The design of the robot enables it to reconfigure and propel itself through a 150-mm access port, as well as reconfigure itself to navigate through narrow pathways [see Fig. 1(c) and (d)]. The contributions of this article are as follows:

1) the mechatronic design of a novel reconfigurable mecanum-wheel-driven robot;
2) controllability analysis for reconfigurable mecanum-wheel-driven robot;
3) demonstration and analysis on the basic capabilities of the robot;
4) deployment in Sellafield’s Magnox facility.

The rest of this article is organized as follows. Section II reviews related work on reconfigurable robots that have the potential to address the 150-mm access port challenge. Section III presents the hardware design of the robot. Section IV
presents the kinematic and dynamic models used for the controllability proofs in Section V, as well as the feedback control used for trajectory tracking. Section VI demonstrates omnidirectional capability (controllability) for nonstandard mecanum wheel configurations through a series of experiments and ingress of 150-mm access port,1 as well as limitations of the robot. Section VII details the deployment of the robot in the Magnox facility in Sellafield and lessons learned. Finally, Section VIII concludes this article.

II. RELATED WORKS

A comprehensive review of ground mobile robots used in the nuclear industry is presented in [2]. Many of these environments are highly cluttered due to machinery, and there are often areas that cannot be explored using traditional platforms due to their size. This is further compounded by the restriction on the access port for accessing such facilities to 150-mm diameter. With these restrictions in place, the choice of using reconfigurable robots, though more complicated, can address these difficult restrictions.

A. Reconfigurable Robots

In a recent case study [4], Sarcos’ Guardian S reconfigurable robot was used to inspect a dust extraction system, reducing both risk to employees and manufacturing downtime. Another example was developed by Tokyo Electric Power Company (TEPCO) [3]. Their robot was designed to take a tubular form when traversing down the narrow pipe. Once clear of the pipe, the robot expands into a U shape for stability, similar to fixed-configuration tracked robots, to carry out the inspection task.

Other forms of mobile robotic platforms that have been used for restricted access environment exploration, though may not specifically fulfill the access port requirement in this study, are modular reconfigurable [5] and snake-type robots [6]. Modular reconfigurable robots consist of multiple detachable modules that can either be similar in design and capability (homogeneous) [7], [8] or dissimilar (heterogeneous) [9]. The latter enables a larger variety of payload or functionality to be deployed simultaneously [10], [11]. These modules can be combined in a variety of shapes to meet the required demands such as stair-climbing [12] and stepping over obstacles [13].

However, reconfigurable robots present additional challenges in the design and application. The mechanical and control system is evidently more complex compared to a reconfigurable robot. The connection mechanism for mechanical linkage, power, and communication between modules needs to be robust and supports the required communication bandwidth, especially where high-speed communication is required. In hazardous environment, operating the robot with a tether provides a way of full retrieval of the robot in the event the robot is rendered inoperable due to radiation damage or unforeseen circumstances [14]. Using modular reconfigurable robots introduces the possibility that damaged modules detached from the main body become irretrievable.

The structure of the snake-like robot typically consists of a serial chain of nondetachable modules connected through an actuated joint. The motion of such robots depends on the drive mechanism employed. For bioinspired approaches, each module has at least an actuated rotary motion. Motion is achieved through undulation along the robot’s body, enabling motion in both open area [15] and in the presence of obstacles [16], [17]. Alternatively, modules with a drive mechanism, such as track [18] or wheels [19], enable motion without undulation of the body.

In general, reconfigurable robots capable of fulfilling both the access requirements and have the capability for large sensor payloads are limited in the literature. The size of the modules generally limits the available payload size and mass. The actuation mechanism used for realizing motion, for example undulation of the robot’s body, further restricts feasible mounting locations for sensor payloads. Such robots are especially valuable for nuclear environments, as seen by the case study from TEPCO.

B. Controllability of Mecanum Wheels

The use of mecanum wheels in a reconfigurable manner deviates significantly from the literature and commercial robots. Mecanum wheels are commonly arranged in a rectangular shape, where the rollers form an X-shape when viewed from above (see Fig. 2) [20], [21], [22]. The same arrangement is observed for platforms with more than four wheels [23]. More recently, mecanum wheels arranged in a straight line have been proposed [24], [25]. Compared to ballbots [26] that have a single contact point with the ground and are nonholonomic, a straight line configuration with mecanum wheels has a larger number of contact points and is holonomic.

With regard to the controllability of using mecanum wheels, arranged in an either standard or nonstandard shape, this criterion has been evaluated either using the velocity Jacobian [27], [28], linearized dynamics [29], or by heuristics, using

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1A video of the experiments is available in the supplementary material.
Fig. 2. Mecanum wheel arrangements. (a) X-configuration (standard). (b) O-configuration. (c) Straight line configuration.

Fig. 3. (Left) Main elements of the MIRRAX: body, legs, wheel, and joint assemblies. (Right) Arm assembly.

TABLE I
GENERAL SPECIFICATIONS OF THE MIRRAX ROBOT

| Description               | Value                          |
|---------------------------|-------------------------------|
| External dimensions       | (L x W x H)                   |
| (U-configuration)         | 0.58 m x 0.51 m x 0.13 m      |
| (Straight-line configuration) | 0.140 m x 0.13 m x 0.13 m   |
| Weight                    |                               |
| Body + Arm                | 3.1 kg                        |
| Leg 1                     | 0.7 kg                        |
| Leg 2                     | 0.8 kg                        |
| Wheel (each)              | 1.15 kg                       |
| Joint (each)              | 0.3 kg                        |
| Total                     | 9.8 kg                        |
| Payload size              | Up to 80 mm x 240 mm          |
| Payload weight            | Max 2kg                       |
| Communication interface   | Wireless or tethered          |
| Battery/run-time          | 2 hours                       |
| Maximum velocity          | 0.78 m/s                      |

The design of the arm enables a larger payload mass to be attached to its end compared to an articulated arm. Having the capability to raise and lower the arm serves two purposes. First, the overall height of the robot can be adjusted for the 150-mm port ingress or overhanging obstacles. Second, the direction and height of the sensor can be adjusted for improving the quality of data collected.

For robustness, MIRRAX’s body, legs, joints, and wheel hubs are constructed from custom-made aluminum parts. The hollow mecanum wheels are also custom made, using 3-D-printed parts.

A. Locomotion and Articulation

MIRRAX’s mecanum wheels run on bespoke hollow axle hubs, allowing space for the servo motors to sit inside the wheels and for the wiring loom to run through the center of the robot [see Fig. 4(a)]. The wheels are connected to the hub via thin profile sealed roller bearings. MIRRAX’s wheels are driven by velocity-controlled servo motors with toothed gears attached to their horns. The toothed gear drives an internal ring gear that is fixed to the inner radius of the wheel with a 3:1 reduction ratio. The maximum linear velocity of MIRRAX is 0.78 m/s; this limit is a result of the maximum velocity of the Dynamixel XM430-350T servo motors used and the requirement for hollow wheels leading to the use of a ring gear. Despite the low maximum velocity, these particular servo motors were selected for their size, power consumption, reliability, and ease of integration.

The joints of MIRRAX are actuated in a similar way, using matching servo motors and an internal ring gear [see Fig. 4(b)]. The key difference is that the servo motors in the joints are operated in position control mode rather than velocity control to enable the joint angles to be regulated. The gearing ratio between the Servo motor and the joint is also 3:1.

B. Electronics Architecture

Fig. 5 shows a schematic of the layout of, and interconnections between, the electronic components inside MIRRAX. A description of the electronic architecture follows.

MIRRAX is powered by a 4-Ah 11.1-V lithium polymer battery housed in Leg 1. At full charge, the battery capacity enables the robot to be operated for approximately 2 h. Alternatively, the robot can be operated indefinitely using a tether for both power and communication. Alongside the battery, Leg 1 houses the power board for the servo motors, ON/OFF switches, and the charging port.
All the computational components are housed in Leg 2. The main computation unit is a single-board PC running Linux and Robot Operating System (ROS). All of the software for MIRRAX is written in C++ and is deployed within the ROS architecture. Any external connected computers are used for sending simple messages such as position estimates, waypoints, or velocity commands if MIRRAX is under manual control. In addition to the single-board PC, Leg 2 houses the servo communication board, the actuator driver for the arm, and the Wi-Fi antennas. MIRRAX can connect to external control computers using either WiFi or Ethernet via a tether.

The body element of MIRRAX is used to store the sensor payload; this will include both sensors for navigation and any sensors that will be used for surveying or monitoring tasks. Sensors in the body element are attached to an articulated arm that rises vertically from the body section. The default sensor package is a rotating LiDAR for navigation and 3-D reconstruction paired with a collimated cadmium zinc telluride gamma-ray and X-ray detector.

IV. ROBOT MODELING AND CONTROL

The derivation of the kinematic and dynamic model of a reconfigurable mobile robot with mecanum wheels here extends upon the well-established literature on their fixed configuration counterpart [27], [28], [29], [30], [31]. The annotations for the MIRRAX robot are shown in Fig. 6. The inertial and base frame are labeled as \( F_I \) and \( F_b \), respectively. The frame, \( F_r \), corresponds to the robot’s geometrical center between the wheels. The wheel frames on each leg link are labeled \( W_1 \) to \( W_4 \). The robot has two leg links attached to its base link via joints \( \phi_1 \) and \( \phi_2 \).

The generalized coordinates of the robot are defined as

\[
q = [p_x, p_y, \theta, \phi_1, \phi_2, \sigma_1, \ldots, \sigma_{n_w}, \psi_1, \ldots, \psi_{n_w}]^T
\]

where the first three terms are the \( x \) and \( y \) coordinates of the base and the rotation angle \( \theta \) between the axes \( x_b \) and \( x_I \), \( \phi \) is the leg’s joint angle, and \( \sigma_i \) and \( \psi_i \) are the wheel and roller angular position, respectively, for wheel \( i = \{1, \ldots, n_w\} \), where \( n_w \) is the number of wheels of the robot; in this case, \( n_w = 4 \). A more compact form for the reduced generalized coordinates for the robot is expressed as

\[
x = [p_x, p_y, \theta, \phi_1, \phi_2]^T.
\]

The robot is actuated by changing either the velocity or torque for each wheel and leg joints. Therefore, the control input vector for velocity and torque control are defined, respectively, as

\[
u_v = [\dot{\sigma_1}, \dot{\sigma_2}, \dot{\sigma_3}, \dot{\sigma_4}, \dot{\phi}_1, \dot{\phi}_2]^T
\]

\[
u_\tau = [\tau_{\sigma_1}, \tau_{\sigma_2}, \tau_{\sigma_3}, \tau_{\sigma_4}, \tau_{\phi_1}, \tau_{\phi_2}]^T.
\]

A. Velocity Mapping

The velocity mapping between the reduced generalized velocities, \( \dot{x} \), and the wheel velocity, \( \dot{\sigma} \), is first derived followed by the full mapping between \( \dot{x} \) and \( \dot{u}_w \).

The no-slip and rolling constraints of the roller’s point contact, \( c \), as shown in Fig. 7, for an arbitrary wheel, is expressed as follows:

\[
w v_c \cdot \hat{u}_s = 0 \quad (1)
\]

\[
w v_c \cdot \hat{u}_r = \psi r_r \quad (2)
\]
where \( \omega \mathbf{v}_c \in \mathbb{R}^3 \) is the linear velocity at \( c \), \( r_r \) is the roller radius, and \( \hat{u}_w \in \mathbb{R}^3 \) and \( \hat{u}_r \in \mathbb{R}^3 \) are the unit vector, expressed in the wheel frame, for the no-slip and rolling direction, respectively. For generality, the subindices have been excluded in Fig. 7.

The linear velocity at the wheel frame, \( \mathcal{W} \), due to both the base frame linear and angular velocity, and the leg joint angular velocity, \( \phi \), expressed in the robot’s base frame and wheel frame, respectively, is defined as

\[
\mathbf{v}_w = R_z^T(\theta) \begin{bmatrix} p_x \\ p_y \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \dot{\phi} \end{bmatrix} \times p_{bw}(\phi) + \begin{bmatrix} 0 \\ 0 \\ \dot{\phi} \end{bmatrix} \times R_z(\phi) p_{w}\bar{w},
\]

(3)

where \( R_z(\cdot) \in SO(3) \) is the rotation matrix about the \( z \)-axis, \( p_{bw}(\phi) \in \mathbb{R}^3 \) is the position vector from the base to wheel frame, and \( p_{w\bar{w}} \in \mathbb{R}^3 \) is the position vector from the leg joint to the wheel frame.

The linear velocity at \( c \) due to the wheel angular rotation, \( \dot{\sigma} \), and the linear velocity from the base frame, \( \omega \mathbf{v}_w \), expressed in the wheel frame, is given by

\[
\omega \mathbf{v}_w = \omega \mathbf{v}_w + \dot{\sigma} \hat{e}_y \times p_{wc},
\]

(5)

where \( \hat{e}_y \) is the unit vector in the \( y \)-axis.

Substituting (5) into both (1) and (2) and rearranging yields

\[
\begin{bmatrix} \dot{\sigma} \\ \dot{\psi}_w \end{bmatrix} = \begin{bmatrix} d_w \\ d_r \end{bmatrix} \dot{x},
\]

(6)

where \( d_w, d_r \in \mathbb{R}^{1 \times 5} \).

The mapping from \( \dot{x} \) to the wheel and roller angular velocities explicitly requires the wheel attached to the leg joint to actively rotate when the leg joint moves to prevent dragging.

Stacking (6) for each wheel and rearranging yields

\[
\begin{bmatrix} \dot{\sigma}_1, \ldots, \dot{\sigma}_4, \dot{\psi}_1, \ldots, \dot{\psi}_4 \end{bmatrix}^T = \begin{bmatrix} D_w \\ D_r \end{bmatrix} \dot{x},
\]

(7)

where \( D_w, D_r \in \mathbb{R}^{4 \times 5} \) (see the Appendix for the full equation).

Since the rollers are passive and not controllable, only the top half of (7) is required for the inverse mapping between the velocity control input and the reduced generalized velocities, which is given by

\[
\mathbf{u}_w = \begin{bmatrix} D_w \\ 0_{2 \times 3} \end{bmatrix} \begin{bmatrix} \dot{x} \end{bmatrix} \triangleq \mathbf{A} \dot{x},
\]

(8)

where \( \mathbf{A} \in \mathbb{R}^{6 \times 5} \).

The inverse mapping in (8) is expressed with respect to the base frame, \( \mathcal{F}_b \). It may be desirable to control the robot about its geometrical center, \( \mathcal{F}_c \). In which case, \( p_{bw} \) in (3) is replaced with \( p_{cw} \triangleq p_{cw}(\phi) \), which is the position vector from \( \mathcal{F}_c \) to \( \mathcal{W} \), defined as

\[
p_{bw} = \hat{u}_c \quad \text{and} \quad p_{cw} = p_{bw} - p_{br}.
\]

(9)

The direct mapping between the velocity control input and the reduced generalized velocities is

\[
\dot{x} = \mathbf{A}^+ \mathbf{u}_w,
\]

(11)

where \( (\cdot)^+ \) is the Moore–Penrose pseudoinverse. Since \( \mathbf{A} \) has full column rank, then \( \mathbf{A}^+ \) has full row rank, which implies that the direct mapping (11) is underdetermined and, thus, has infinite solutions given by the set

\[
X = \{ \dot{x} \in \mathbb{R}^n : \dot{x} = \mathbf{A}^+ \mathbf{u}_w + (I - \mathbf{A}^+ \mathbf{A}) z \}.
\]

(12)

The set (12) includes solutions for the reduced generalized velocity \( \dot{x} \) that are in the nullspace of \( \mathbf{A}^+ \). Since only solutions in the range space of \( \mathbf{A} \) is kinematically feasible, (11) should only be used after ensuring that \( \mathbf{u}_w \) is in the range space of \( \mathbf{A} \).

B. Dynamics

Owing to the nonholonomic constraints, the equation of motion has been derived using the Euler–Lagrange of the second kind, namely with Lagrange multipliers for MIRRAX. The equation of motion takes the form

\[
\mathbf{M}(q) \ddot{q} + \mathbf{C}(q, \dot{q}) = \mathbf{B} \mathbf{u}_r + \mathbf{L}(q) \lambda + \mathbf{Q}(q) \ddot{q}.
\]

(13)

The mass inertia matrix \( \mathbf{M}(q) \in \mathbb{R}^{13 \times 13} \) is derived using the kinetic energy of the system. The Centripetal and Coriolis term \( \mathbf{C}(q, \dot{q}) \in \mathbb{R}^{13 \times 13} \) is derived using Christoffel symbols of \( \mathbf{M}(q) \). The friction terms are grouped together in \( \mathbf{Q}(q) \in \mathbb{R}^{8 \times 13} \), while \( \mathbf{B} \in \mathbb{R}^{13 \times 6} \) is a mapping matrix for the actuated joints. The Pfaffian constraint matrix \( \Lambda(q) \in \mathbb{R}^{8 \times 13} \) is obtained by rearranging (7) to take the form of \( \Lambda(q) \ddot{q} = 0 \). Finally, \( \lambda \in \mathbb{R}^8 \) is the Lagrange multiplier from the rolling and no-slip constraints for each wheel.

The Lagrange multipliers are eliminated using the nullspace of \( \Lambda(q) \), defined as \( \mathbf{N} \in \mathbb{R}^{13 \times 5} \), where \( \mathbf{N} \Lambda(q) = 0 \). Multiplying (13) with \( \mathbf{N} \) as appropriate will result in the reduced generalized coordinate system, \( x \), where

\[
\mathbf{M}(x) = \mathbf{N}^T \mathbf{M}(q) \mathbf{N}
\]

\[
\mathbf{C}(x, \dot{x}) = \mathbf{N}^T \mathbf{C}(q, \dot{q}) \mathbf{N} + \mathbf{N}^T \mathbf{M}(q) \dot{\mathbf{N}}
\]

\[
\mathbf{B}_x = \mathbf{N}^T \mathbf{B}
\]

\[
\mathbf{Q}_x(x) = \mathbf{N}^T \mathbf{Q}(q) \mathbf{N}
\]

resulting in

\[
\mathbf{M}(x) \ddot{x} + \mathbf{C}(x, \dot{x}) + \mathbf{B}_x \mathbf{u}_r + \mathbf{Q}_x \dot{x} = \mathbf{B}_x \mathbf{u}_r + \mathbf{Q}_x \dot{x} - \mathbf{C}(x, \dot{x}) \dot{x}.
\]

(14)

which can be solved for the forward dynamics

\[
\ddot{x} = (\mathbf{M}(x))^{-1} \left[ \mathbf{B}_x \mathbf{u}_r + \mathbf{Q}_x \dot{x} - \mathbf{C}(x, \dot{x}) \dot{x} \right].
\]

(15)

C. Control System

To enable trajectory tracking, a feedback controller was employed for the robot’s base velocity. The controller velocity output \( \hat{x}_d \in \mathbb{R}^5 \) for a desired position \( x_d \) and velocity \( \dot{x}_d \) is described by the control law

\[
\hat{x}_c = \dot{x}_d + \mathbf{K}_p (x_d - x)
\]

(16)

where \( \mathbf{K}_p \in \mathbb{R}^{5 \times 5} \) is the diagonal gain matrix.
The resulting \( u \) from (8) using \( \dot{x}_r \) in (16) may not be within the actuator limits. It is not possible to directly impose fixed velocity limits on \( \dot{x}_r \) since the velocity limits are configuration dependent. Furthermore, it is desirable to have the robot travel at a feasible velocity, \( \dot{x}_f \), parallel to \( \dot{x}_c \), i.e., \( \dot{x}_f = \beta \dot{x}_c \), where \( \beta \in [0, 1] \). The above requirement is achieved by solving the following quadratic programming problem at each time step:

\[
\dot{x}_f \in \arg\min_{\dot{x}} \| \dot{x} - \dot{x}_c \|^2
\]

subject to

\[
- u_{\text{lim}} \leq A \dot{x} \leq u_{\text{lim}}
\]

\[
\dot{x} \times \dot{x}_c = 0
\]

where \( u_{\text{lim}} \in \mathbb{R}^6 \) is the actuator velocity limit.

V. CONTROLLABILITY

The controllability of a reconfigurable robot with mecanum wheels is analyzed here using the velocity Jacobian and the linearized dynamics.

A. Velocity Jacobian

In this article, the approaches taken in [27] and [28] are adopted to analyze the controllability of MIRRAX. In [27], a quantitative measure of how good the controllability is provided using the global stiffness index (GSI), \( n_c \) [32]

\[
n_c = \frac{1}{\| C \| \cdot \| C^{-1} \|}
\]

where

\[
C = (W)^T \cdot W, \quad \| C \| = \sqrt{\text{Tr} \left( \frac{1}{3} C C^T \right)}
\]

and \( W \) is the first three columns of the matrix \( D_w \).

A larger GSI would result in better disturbance rejection and better trajectory tracking, whereas having a zero GSI means that the system is uncontrollable. Similarly, Borisov et al. [28] use the condition of having a nonzero determinant as a criterion for controllability, provided that at least three wheels are in contact, defined as

\[
d_c = \det \begin{bmatrix}
\alpha_{11} & \alpha_{21} & \alpha_{31} \\
\alpha_{12} & \alpha_{22} & \alpha_{32} \\
(Jp_1 \cdot \alpha_1) & (Jp_2 \cdot \alpha_2) & (Jp_3 \cdot \alpha_3)
\end{bmatrix} \neq 0
\]

where \( \alpha_i \) is the roller position relative to the robot frame, \( \alpha_i \) is the roller axis direction, and

\[
J = \begin{bmatrix}
0 & -1 & 1 \\
1 & 0 & 0
\end{bmatrix}.
\]

Comparing between Fig. 8(a) and (b), and (c) and (d), it can be seen that the controllability is dependent on the wheels having ground contact. Under the ideal condition where all the wheels are in contact, the robot is controllable for all the joint configurations since both the determinant and GSI are nonzero [see Fig. 8(a) and (b)]. Both these metrics approach zero as \( |\alpha_{1,2}| \to 180^\circ \), the inverted-U shape, implying an increase in susceptibility to disturbance and being less controllable, i.e., taking longer to reach a desired state. However, the possible loss in wheel ground contact for extended periods of time can render the robot uncontrollable as seen by the dark blue regions in Fig. 8(c) and (d), where the determinant and GSI are zero.

The GSI using the robot’s full inverse mapping matrix \( A(x) \) results in GSI \( \approx 0 \) at \( \phi_{1,2} = 0 \) (standard shape configuration), which is markedly different from its fixed-configuration counterpart where GSI = 0.216. This result suggests that the GSI approach is not directly adaptable to include reconfigurability in the controllability analysis used above.
B. Linearized Dynamics

The global controllability for a nonlinear system, as is the case in this study, does not exist as compared to a linear system. A weaker form of this proof is instead show that it is small-time locally controllable (STLC), as shown in [29] for a collinear mecanum drive. A similar approach is used here, namely by evaluating the Kalman controllability matrix (KCM) using the linearized system dynamics at selected state. The KCM should have full rank for the system at the linearized state to be STLC.

For the state vector, \( z = [x, \dot{x}]^T \), the resulting linearization takes the form

\[
\dot{z} = A_L z + B_L u_
\]

(22)

where

\[
A_L = \begin{bmatrix}
0_{5 \times 5} & I_{5 \times 5} \\
0_{5 \times 5} & \frac{\partial D}{\partial \theta}
\end{bmatrix}, \quad B_L = \begin{bmatrix}
0_{5 \times 6} \\
\frac{\partial D}{\partial u}
\end{bmatrix}
\]

and \( D \) is the forward dynamics from (15).

For MIRRAX, the arm configuration of the robot is most likely to affect the controllability of the robot. Hence, the robot’s controllability was evaluated at equilibrium states corresponding to different arm configurations, similar to Section V-A. Stepping through the various joint angle combinations at 5° intervals and evaluating the KCM of (22) resulted in full rank for all the configurations evaluated, namely, \( \text{rank}(\text{ctrb}[A_L, b_L]) = 10 \), suggesting that the robot is at least STLC at these evaluated configurations.

VI. EXPERIMENTAL EVALUATION AND DISCUSSION

This section presents the experimental validation of the robot in achieving 1) ingress and egress through 150-mm-diameter access ports and 2) controlled navigation of confined areas. A video showing the experiments is available. The data supporting the findings reported in this article are openly available from the FigShare repository.2

A. Experimental Setup

The manual control of the robot’s base velocity follows a simple mapping from a PS4 joystick to \((\dot{x}, \dot{y}, \theta)\), similar to ROS 2-D twist commands. Additional velocity commands and functionalities were introduced to actuate the legs and arms (integrating the velocity commands for the legs and arm positions) using the buttons available on the PS4 joystick.

For trajectory tracking, a 5-D trajectory of \( x \) was generated using an adapted version of the ROS mav_trajectory_generation package. The feasibility of the trajectory generated against the wheel velocity limit was checked in an exhaustive manner using (7). In the event that the trajectory violates the wheel velocity limits, the trajectory was scaled in time by the ratio \( s = \omega / \omega_{\text{max}} + 0.05 \) and the feasibility checks repeated until it becomes feasible. A VICON system was used for both ground truth and the feedback controller, which runs at 100 Hz.

B. Limited Access Entry

The primary hardware requirement is for the robot to ingress and egress 150-mm-diameter access ports. A snapshot of this motion is shown in Fig. 9. The robot was first reconfigured to an L-shape configuration [see Fig. 9(b)] and then driven down the access port. As the rear leg approaches the port, it was moved to \( \phi_1 = 90^\circ \) [see Fig. 9(c)]. At the same time, the front leg that has emerged from the port was moved toward its default position as much as possible without colliding with the wall [see Fig. 9(d)]. As the robot continues moving and exits the port completely, the rear leg takes back its default position since the exit area had sufficient clearance.

A scenario that may occur inside or on exiting the port is to have the robot rotate around its \( x \)-axis. In its current state, it is possible to orientate the robot to be right-side up \((\theta_{\text{roll}} = 0^\circ)\) if \(-90^\circ \leq \theta_{\text{roll}} \leq 90^\circ\). The robot becomes unable to orientate itself beyond this range due to the placement of components, which results in mass imbalance. As such, the counter torque from the wheels is unable to rotate the robot’s base back up.

C. Mass Balance

The inherent design of MIRRAX, having both the front and rear legs connected via a link that does not pass through the center of the robot, results in an off-balance center of mass (CoM). The robot’s CoM is not fixed due to the robot’s reconfigurable capability, thus depending on both the legs and arm position. Taking the U-shape (default) configuration as a starting point, the robot’s CoM can be calculated from the mass of the individual links, summarized in Table I.

To address the robot’s off-centered CoM, counterbalance mass was attached to the end of the leg links. The location

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2[Online]. Available: https://doi.org/10.48420/21071017
3[Online]. Available: https://github.com/ethz-ast/mav_trajectory_generation
for the mass attachment was selected due to the limited space available inside the leg links, and the end of the leg having the largest distance from the robot’s geometrical center, i.e., a larger moment arm reduces the mass required. The total mass required for the robot’s CoM to be coincident with the geometrical center was calculated to be 5.44, or 2.72 kg per leg. For the maximum arm payload of 2 kg, a counterbalance mass of 4.24 kg per leg would be required.

The result of having the mass balance is shown in Figs. 10 and 11(left) with the legend weighted where significant improvement is observed on both open- and closed-loop tracking of the desired path. However, the overall mass of the robot is increased significantly, where the counter mass accounts for 36% of the final mass. A possible strategy to circumvent or reduce the use of counter mass used is to utilize a \(Z\)-configuration, as seen by the imposed image of MIRRAX in Fig. 11(right). This configuration indirectly balances the mass of the robot, resulting in the CoM to be coincident with its geometrical center, provided that the mass of both the legs is similar. The resulting trajectory tracking performance using the nonweighted \(Z\)-configuration is comparable with the weighted approach.

Although closed loop does indeed improve the performance especially when operated without the counter mass, there are advantages when the open loop tracks the desired path such as ease of control in the manual mode and lower power consumption since it drifts less. Furthermore, higher accuracy can be obtained from odometry localization as well. It should be noted that the balancing mass used in this experiment was temporary since the mass required depends on the sensor payload on the arm, which, in turn, depends on the mission/research requirement. Hence, the counter mass was left as an ad-hoc solution here and will be modified in the future accordingly.

D. Robot Balance

As the robot approaches the straight-line configuration \(\phi_1 = -\phi_2 = 90^\circ\), it becomes dynamically unstable and susceptible to rolling over. Although it was possible to employ controllers capable of both balancing and moving the robot at this configuration [29], the decision was taken to avoid this configuration during operation, except for the ingress and egress from the access port. This was due to the risk of rolling over during operation, which can cause the robot to be unable to right itself, as discussed in Section VI-B, and from crashing, which can have detrimental effect on the sensors located on the arm.

A selected number of configurations were evaluated to characterize the minimum stable footprint using the robot’s roll and absolute trajectory error (ATE) as quantitative measures. The configurations explored were generally based on a trapezoidal and \(Z\)-shape (see Fig. 12): the first when both \(|\phi_1, \phi_2| > 90^\circ\) (trapezoidal) and the second when \(\phi_1 < 90^\circ\) and \(\phi_2 < -90^\circ\) (zig-zag).

Fig. 13(top) shows the roll angle from executing a motion where the orientation of the robot and inertial frames were fixed and aligned, while the direction of motion was not aligned to the body frame \(x\)-axis [see Fig. 13(bottom)]. Table II summarizes the result for the different configurations evaluated.

![Table II](image)

Table II: Quantitative Assessment of Different Configurations for Minimum Stable Footprint

| Configuration | Width, m | Max (Roll), ° | \(\sigma\), ° | ATE, m |
|--------------|---------|--------------|----------|-------|
| (85, -85)    | 0.15    | 13.79        | 3.35     | 0.27  |
| (80, -80)    | 0.19    | 4.82         | 0.84     | 0.17  |
| (75, -75)    | 0.22    | 2.46         | 0.54     | 0.26  |
| (70, -70)    | 0.26    | 1.96         | 0.44     | 0.12  |
| (85, -95)    | 0.14    | 22.53        | 6.99     | 0.34  |
| (80, -100)   | 0.16    | 15.08        | 2.35     | 0.32  |
| (75, -105)   | 0.17    | 5.68         | 1.20     | 0.22  |
| (70, -110)   | 0.19    | 3.42         | 1.05     | 0.11  |
| (65, -115)   | 0.21    | 3.74         | 0.69     | 0.13  |
| (75, -115)   | 0.19    | 1.93         | 0.69     | 0.16  |
| (70, -120)   | 0.21    | 1.85         | 0.57     | 0.16  |

It can be observed from Fig. 13(top) and Table II that both the magnitudes of the undesirable roll and ATE was especially significant near the straight line configuration: (85,−85) and (85,−95). This was due to these two configurations being close...
Fig. 13. (Top) Magnitude of base roll at various configurations for assessing minimum stable footprint. (Bottom) Trajectory tracking at various configurations experiencing wheel slippage at a similar spot.

The roll and ATE reduced significantly for the subsequent configurations, with the largest improvement observed at (80, −80) and (75, −105). For the remaining configurations, only slight improvements in the reduction of roll was observed, although the Z-shape gained a larger improvement in tracking with a smaller ATE, \( \leq 0.13 \) m. The (75, −75) configuration had a larger ATE error due to significant wheel slippage observed during the motion. It was expected that the ATE would fall between 0.17 and 0.12 m under no slip conditions.

The Z-shape configurations do not result in better performance compared to the trapezoidal shape at footprint width of less than 0.19 m. However, the performance changed as the width increased, where the Z-shape achieved better tracking and less roll compared to its counterpart. The minimum 90° corner path width that MIRRAX can fit through was approximately 0.3 m (horizontal width). Assuming that the path leading up to the corner is of a similar size, the configurations (75, −115) and (70, −120) would yield a better choice. This selection provides larger wall clearance and similar quantitative metric compared to the (70, −70) configuration.

An interesting observation on the minimum footprint experiments was that the robot was sometimes unable to progress along the desired trajectory due to wheel slippage. This scenario was observed to occur at a similar area for the different experiments carried out (see Fig. 13(bottom) for the stuck region). Increasing the controller gains and leaving it to continue attempting to reach the goal position failed with it remaining in the same spot. Although not shown here, the robot was made to escape this slippage by inducing motions in other directions, e.g., sideways then forward instead of a pure diagonal motion. This scenario highlights the susceptibility of being stuck due to wheel slippage, similar to other types of wheeled robots. However, the capability for omnidirectional motion in this case allows for additional motions to be used to escape from being stuck.

E. Controllability

Using the proofs presented in Section V, the robot was theoretically controllable over its full range of motion. The practicality of this was evaluated on a number of experiments. Fig. 14 shows the robot tracking a predefined trajectory with either fixed- or dynamic leg configurations. Fig. 14(a) shows a representation of omnidirectional motions. Fig. 14(b) shows the robot navigating through a narrow path. In general, the robot was able to track the prescribed trajectory closely, where the error magnitude for the \( xy \) position and orientation was less than 0.018 m and 0.6° at any time instant for both motions.

The robot was further evaluated by attempting to navigate through cluttered and confined environments via manual control mode. Fig. 15 shows a snapshot of the robot’s motion navigating through a 90° corner accessible only through narrow pathway. The control of the robot without the counter mass was possible and was generally responsive as seen in Fig. 15 and the supplementary video.

There were instances where the wheel lost traction due to the mass balancing issue discussed previously in Section VI-C. This was observed while navigating the corner that required the robot to take on a configuration close to (45, −45), which was known to cause loss of controllability. However, by perturbing the robot’s motion and adjusting the legs, it was possible to navigate through the corner. The Z-shape was also used where possible to minimize the robot’s roll during motion.

4The start and goal positions are the same.
VII. SELLAFIELD DEPLOYMENT

A version of the MIRRAX robot was deployed into a real-world low-level radioactive facility on the Sellafield site, U.K., in March 2018. The deployment area was part of the Magnox reprocessing facility, which had been sealed for a number of years and was the first time a mobile robot had been deployed into this facility. The purpose of the deployment was to geometrically characterize the area so that decommissioning plans could be generated. A video of the deployment is available.\(^5\)

The robot used in the deployment was largely similar in design with minor differences: the robot’s links were constructed from PVC and 3-D-printed parts and the arm consisted of an actuated articulated joint with a pan unit. The CoM for the robot used in the deployment was closer to its geometrical center due to the materials used being lighter. The mass of the wheels was larger than the rest of the links, enabling self-righting from arbitrary roll angles.

The arm design differed from the robot presented earlier in Section III since the payload used in the deployment was lighter. The sensor payload consisted of two 2-D LIDARs attached to a pan unit, enabling 3-D mapping while still being able to localize using the forward facing LIDAR. An RGB camera located at the edge of the front leg enabled visual feedback for the operator.

The robot was tethered and operated manually, with the tether being used for both power and communication to the base PC. An RGB camera enabled a colored view of the facility [see Fig. 16(a) and (b)]. Inside the facility, the robot utilized its forward-facing LIDAR for 2-D simultaneous localization and mapping as it was driven forward for inspection and mapping. After traveling for short intervals, the robot was stopped, and the pan unit was rotated to increase point cloud data collection from the top-facing LIDAR. The point cloud collected was postprocessed offline; the final render of the facility is shown in Fig. 16(c).

At the end of the mapping session, the LIDAR units were retrieved, and the rest of the robot was disposed as low-level radioactive waste. The overall deployment successfully proved the feasibility of both MIRRAX and in general mobile robotic platforms being used for remote inspections in these hazardous environments.

VIII. CONCLUSION

This article presented MIRRAX, a reconfigurable robot driven by mecanum wheels. Special focus was given to its design to enable it to have sufficient payload capability as well as fit through a 150-mm-diameter access port. The incorporation of a feedback controller was shown to enable trajectory tracking for arbitrary leg configurations. Preliminary experiments confirmed the robot’s capability for 150-mm-diameter access port entry and omnidirectional capability. The validation experiments also highlighted certain limitations, such as the off-balance CoM, wheel slippage, rolling during motion, and recovery when MIRRAX operates around the straight-line configuration. The robot was subsequently deployed in the Magnox facility on the Sellafield site, showcasing the relevance of the robot in practical scenarios and providing valuable insight of the facility for the site operators.

The preliminary experiments and deployment highlights that a number of challenges remain in both robot development and deployment. Although the modeling and controllability analysis of the robot shows the feasibility of such a design in meeting the requirements for restricted access, disturbances to the system, which were not modeled or difficult to model, can affect the actual use of the system. Real-world scenarios as seen in the experiment and deployment where the environment has irregular terrain from loose gravel, rocks, and obstacles at times result in the robot being stuck, requiring a change in leg configurations or some form of maneuver by the teleoperator to escape from the state it is in. Indeed, the manual control of the six degrees of freedom simultaneously is very challenging, and current teleoperation procedures limit configuration changes to when the robot is static.

The outlook for the robot is to introduce autonomy for operations in unknown environments. Future hardware development will investigate the integration of perception sensors for environment and radiation mapping, both of which are critical for high-level planners and the robot’s controller in ensuring the

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\(^5\)Deployment video. [Online]. Available: https://tinyurl.com/mvewxx9w
robot’s safety and ensuring that the desired motion is executed as expected. A motion planner that is capable of generating a collision-free path is currently being developed [34] but is beyond the scope of the work presented in this article. Not limited to the hardware, there is scope in improving the control system to avoid configurations, which lead to the robot’s wheel losing traction, i.e., autonomously selecting configurations that have a CoM close to the robot’s geometrical center while adhering to other constraints, such as actuator limits and obstacle avoidance.

**APPENDIX**

**CONTROL INPUT TO CONFIGURATION MAPPING EXPANSION**

\[ D_w = E \]

\[ D_r = 1/r_e \]

where \[ E = \text{diag}(f_{w_1}c_{α_1}, \ldots, r_{w_4}c_{α_4}) \]

\[ \alpha_i = \alpha_i + φ_i + θ_i \]

and \[ b_i = α_i + φ_i \]

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Keir Groves received the first-class M.Eng. degree in mechanical engineering and the Ph.D. degree in mechanical dynamics from the University of Manchester, Manchester, U.K., in 2007 and 2011, respectively.

He is currently a Research Fellow with the Department of Electrical and Electronic Engineering, University of Manchester. In 2017, he moved into Robotics and developed MallARD, the group's autonomous aquatic surface vehicle, with the University of Manchester, where he became a Research Fellow in 2019 and specializes in the localization and control of autonomous aquatic robots for use in confined environments.

Simon Watson received the M.Eng. degree in mechatronic engineering and the Ph.D. degree in electrical and electronic engineering from the University of Manchester, Manchester, U.K., in 2008 and 2012, respectively.

He is currently a Reader in Robotic Systems with the Robotics for Extreme Environments Group, The University of Manchester. His research interests include the development of robotic systems (aerial, aquatic, and ground) for the inspection, maintenance, and repair of critical energy generation infrastructure assets.

Horatio Martin received the M.Eng. degree in robotics from the University of Plymouth, Plymouth, U.K., in 2013.

He was a Research Associate with the University of Manchester, Manchester, U.K. His research interests include the hardware design and control of mobile robots.

Ognjen Marjanovic received the bachelor’s (first-class Hons.) degree in electrical and electronic engineering, and the Ph.D. degree in the field of model-predictive control from the University of Manchester, Manchester, U.K., in 1998 and 2002, respectively.

He is currently a Reader in Control Systems with the University of Manchester. He has more than 15 years of experience working on the development and application of control and condition monitoring systems in various process industry sectors, including specialty/fine chemicals and pharmaceuticals, as well as electrical power networks and robotics.

Harriet Peel received the M.Eng degree in aerospace, aeronautical, and astronautical engineering from the University of Bristol, Bristol, U.K., in 2005, and the Ph.D. degree in civil engineering from the University of Leeds, Leeds, U.K., in 2019.

Her research interests include robotics and artificial intelligence.

Barry Lennox received the B.Eng. degree in chemical engineering and the Ph.D. degree in control systems from Newcastle University, Newcastle upon Tyne, U.K., in 1991 and 1996, respectively.

He is currently a Professor of Applied Control with the University of Manchester, Manchester, U.K. His research interests include the development of robotic systems that can used in extreme environments, with nuclear being a particular focus of his work.

Dr. Lennox is a Fellow of the Royal Academy of Engineering and holds a Royal Academy of Engineering Chair in Emerging Technologies.