A Reconfigurable Rolling Mobile Robot with Magnetic Coupling as New Non-prehensile Manipulation Problem

Ollie Wiltshire and Seyed Amir Tafrishi

***Abstract*— This paper presents a new type of mobile rolling robot module as a platform for non-prehensile manipulation and the control challenges involved in accurate control of the robotic system. The designed robot modules include a novel internally actuated magnetic-pendulum coupling mechanism, which presents an interesting control problem involving the frictional/sliding and magnetic effects between each of the modules.**

I. Introduction

Reconfigurable robots, composed of multiple modules that can interact and reconfigure, often lack versatility and independent movement. Coupling rolling robots as modular components addresses this issue by enabling displacement through internal actuation [1], [2]. However, developing coupling mechanisms without external components remains a significant challenge [3], [4]. Controlling these robots could also be difficult due to properties of non-prehensile manipulation, where modules can slip and lose their state during movement. Accurate control requires predicting these dynamics.

Modular Self-Reconfigurable Robots (MSRRs) [3] are mobile robots made up of individual modules containing controllers, sensors, and actuation systems. These modules can reconfigure, enabling MSRRs to perform diverse tasks and navigate unpredictable environments [5], [6]. Modules connect via docking systems, such as mechanical surfaces, magnetic interactions, and grippers, including hybrid combinations. Reconfiguration can occur autonomously or manually. MSRRs are invaluable in search and rescue, environmental monitoring, and hazardous environments due to their modular and reconfigurability nature, which allow them to adjust their morphology for optimal stability and manoeuvrability [6], [3]. Using a modular rolling robot at the centre of the reconfigurable system could be beneficial, as rolling motion offers an effective option [7]. However, developing an appropriate coupling method between rolling modules remains an open challenge.

Rolling robots, during motion, don't remain fixed to the surface and are subject to slippage, causing a loss of state [4]. This issue requires predicting the dynamics for accurate control, introducing a new challenge in non-prehensile manipulation. Non-prehensile manipulation, involving no direct grasp of the object [8], [4], presents significant control difficulties due to slippage and friction, leading to unpredictable dynamics. Previous research has explored rolling and balancing disks [9] and controlling a disk on a beam [10], highlighting the complexities in non-prehensile manipulation. Our study addresses these challenges by introducing internally actuated modular disk modules, unlike existing approaches relying on external actuation which opens great application potentials in swarm reconfigurable robotics. The literature does not adequately address the complexities of independently rotating modular disk bodies in both mechanism design and control. This paper showcases new motion control challenges posed by modular mobile disk robots, contributing to future non-prehensile manipulation solutions in application-based scenarios.

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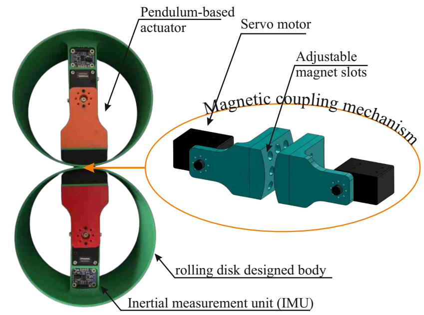
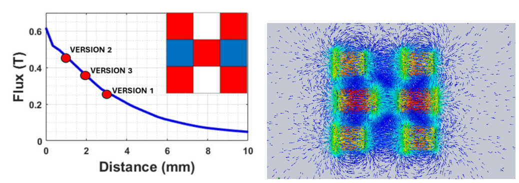


Fig. 1. Robot design with magnetic coupling while balancing.



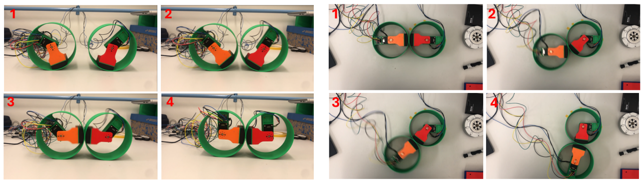
(a) (b)

Fig. 2. a) Simulation results for magnetic flux versed different distances Blue = Positive / Red = Negative Pole) b) Magnetic flux formation

This paper introduces a novel internalized pendulum-based magnetic coupling mechanism for rolling reconfigurable disk robots, investigates magnetic coupling configurations for pendulum-actuated disk modules, and demonstrates the robot's distinctive motion capabilities using scenario-based PD controllers. Additionally, it presents and discusses a new reconfigurable robotic platform designed to address a new control problem in non-prehensile manipulation.

II. Reconfigurable Rolling Robot Design

This section showcases the design of the robot modules and the magnetic coupling mechanism within. The modular robot's main body design features a Dynamixel XM430 high-precision servo motor at the centre, connected to a pendulum-based docking system, as shown in Fig. 1. To demonstrate basic behaviours and analyse coupling, the model is simplified to a disk configuration with two independently operating modules, each using a 1-DoF motor. Additional bodies can



(a) (b)

Fig. 3. Video snapshots of a) coupling motion controlled with PD controller b) fixed link motion controlled with basic PD controller.

be incorporated by attaching passive magnets in various alignments or by adding extra motors to increase degrees of freedom (DoF). This study focuses on motion behaviours such as coupling, spinning, and rolling due to friction, introducing a new platform for non-prehensile manipulation [4]. The robot is controlled by an Arduino interfacing with an IMU sensor using a Kalman filter.

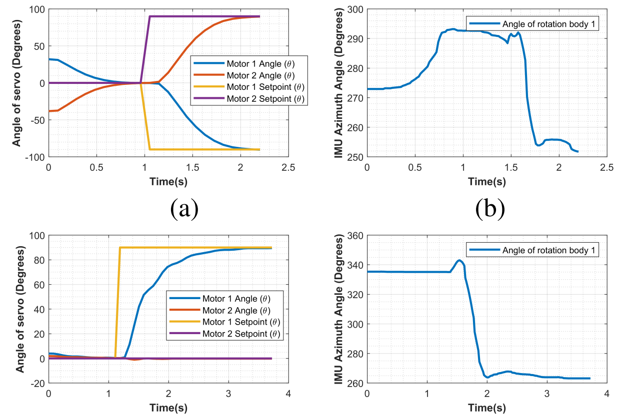
To explore coupling connections using permanent magnets, we studied various magnetic configurations to determine the optimal distance and arrangement for the strongest coupling. Additionally, during the decoupling action, the magnets enable successful detachment, as shown in Fig. 2. We chose the final "H" array configuration with reversed polarity for the outer centre magnets. This adjustment maximised magnetic flux at close distances while facilitating easier decoupling due to a consistent flux density decrease with distance.

III. Motion Study

This section provides an analysis of the current motion capabilities of the designed robot, utilising a PD controller for actuators.

In the first test, we examined independent pendulum-based motion. The design utilizes a pendulum actuator controlled to rotate by θ_i degrees, causing the body to rotate in the opposite direction due to angular momentum conservation. Once the pendulum reaches the physical stop, the disk rolls further. Results show the PD-controlled pendulum successfully follows the desired rotations, but mass imbalance allows relative rotation of the entire body. However, high-velocity motions complicate positioning due to angular momentum, indicating the need for more advanced controllers.

The pendulum-based magnetic coupling system enables various motion patterns and coupling mechanisms. The mass imbalance propels the disk modules, allowing coupling beyond the magnets' effective area (Fig. 3). This is crucial for reconfigurable systems, therefore allowing re-connection if separation occurs during operation. The system also functions as a fixed link, allowing one module to rotate another about its sphere when fixed. Additionally, different motion patterns arise when servos rotate in opposing or the same directions (Fig. 3), enabling reorientation and reconfiguration through relative disk movement rather than entire module displacement. The results of robot motion for each module are depicted in Figs. 4 (a)-(b). This highlights the system's potential for adaptable and complex tasks. A final test was made to self-balance two modules on top of each other, as shown in Fig. 1 which works as a non-prehensile manipulation problem. Furthermore, this property can be seen in Fig. 4-(d) as the motor reaches its set point though the rotation of the body failed to achieve its endpoint due to the frictional nature between the the bodies.



(a) (b) (c) (d)

Fig. 4. Coupling mode: the top figures are a) the results of angular motion for two modules, b) IMU data for moving module. Joint mode: the bottom figures are c) the results of the angular motion of the module and d) IMU data for the actuated module

IV. Conclusion

This paper introduces a reconfigurable rolling disk robot with a pendulum-based coupling system, presenting a new non-prehensile manipulation problem. It demonstrates diverse behaviours, including independent pendulum-based rotation and module coupling, highlighting adaptability for modular robot swarms. This work addresses the challenge of non-prehensile manipulation and lays the groundwork for future systems to dynamically adapt to various tasks. Future research will refine control algorithms, implement energy-based robust controllers for advanced functionalities like balancing and movement simulations, and enhance the coupling mechanism for increased degrees of freedom.

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