# Design and Evaluation of Two Spherical Systems for 3D Mapping*

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## I. Introduction

In recent decades, robotics has evolved from a niche discipline into a transformative technology impacting a wide range of industries, including manufacturing, healthcare, space exploration, and personal assistance. Among the diverse types of robotic systems, spherical robots have recently begun to attract increased attention from researchers. These robots represent a relatively unconventional design compared to more familiar, rotation-restricted systems such as UAVs, handheld devices, and wheeled vehicles.

Unlike traditional wheeled or legged robots, spherical robots offer several key advantages, including omnidirectional movement, enhanced maneuverability in unpredictable environments, and improved protection for internal components. These features make them well-suited for a variety of applications such as surveillance, inspection, environmental monitoring in hazardous conditions, and search-and-rescue operations. Their spherical design enables them to access environments that are difficult or impossible for other robotic systems to navigate, such as steep tunnels, underground mines, narrow passageways, and other confined or dangerous spaces. The sealed outer shell of a spherical robot provides full protection against dust, hazardous chemicals, liquids, and external impacts. Recent research has focused on developing more robust motion mechanisms [1]–[3] and incorporating technologies like LiDAR for 3D mapping, further expanding their capabilities in complex and unpredictable environments [4]–[6].

This research focuses on the development and evaluation of two custom-built spherical robots (see Fig. 1) equipped with advanced LiDAR-based SLAM systems. Both systems integrate Fast-LIO2 [7], Fast-LIVO2 [8], and DLIO [9]—state-of-the-art LiDAR-inertial odometry algorithms known for their real-time performance and accuracy. In the next section, we review recent advancements in spherical robot design and the latest developments in SLAM for spherical platforms, with a particular emphasis on LiDAR-inertial methods. This is followed by a detailed description of the hardware implementation of the two spherical robots developed in this research. Subsequently, we describe the software integration, outlining the implementation of Fast-LIO2, Fast-LIVO2, and DLIO, as well as the motion control mechanisms used for the actuated sphere. Finally, we provide a comprehensive evaluation, comparing the proposed systems with existing solutions in terms of physical performance and mapping quality.

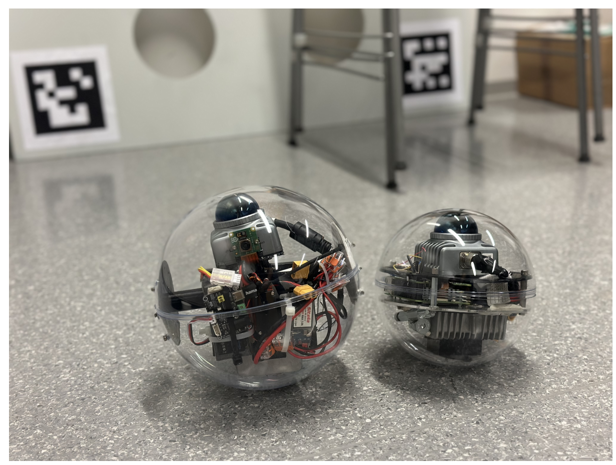

Fig. 1. (Left:) 20cm∅ Actuated Sphere. (Right:) 16cm∅ Non-actuated Sphere.

## II. State of the Art

### A. Spherical SLAM

Spherical Simultaneous Localization and Mapping (SLAM) is an emerging area within mobile robotics, offering promising solutions for robust mapping in constrained or hazardous environments. Unlike traditional platforms, spherical robots encapsulate their sensors within a protective shell and rely on rolling locomotion. This unique configuration introduces both opportunities and significant challenges for SLAM algorithms. One of the earliest spherical SLAM prototypes was L.U.N.A. [10] , which employed a 2D LiDAR and IMU inside a rolling spherical shell. The design validated the feasibility of spherical SLAM. It also featured actuation through internal flywheels, using an IBCOAM (Impulse by Conservation of Angular

Identify applicable funding agency here. If none, delete this.

Momentum) mechanism. A major milestone in this field was the DAEDALUS project [5], funded by the European Space Agency, which proposed a fully enclosed spherical robot for the autonomous exploration of lunar lava tubes. The robot is suggested to be equipped with LiDAR and internal actuators, and its design focused on resilience to lunar regolith and harsh environmental conditions.

A core challenge in spherical SLAM is the aggressive and non-centered rotation induced by rolling locomotion. These motions produce high angular velocities and dynamic behavior across all principal axes. This significantly degrades pose estimation accuracy and leads to error accumulation in the map. This problem is further compounded by the absence of magnetometer usage—often intentionally excluded due to the unreliability of magnetic field data in planetary environments—which leads to uncorrected yaw drift in IMU-based odometry, especially during prolonged navigation.

To address these issues, Arzberger et al. [4], [6], [11] introduced specialized filtering techniques for spherical systems. Their Delta Filter is a lightweight, real-time, multi-trajectory pose estimation method that fuses unreliable trajectories—such as those from IMUs and stereo visual-inertial odometry (VIO)—into a more robust estimate, without requiring explicit sensor uncertainty modeling. The filter operates on pose changes ("deltas"), uses a probabilistic weighting scheme for translation estimation, and applies rotational interpolation via spherical linear interpolation (Slerp). A follow-up Kalman Filter design extended this approach by incorporating covariance-aware models, enhancing pose estimation accuracy during rapid and complex motion.

Despite these advances, most current spherical SLAM systems still lack precise onboard actuation for controlled repositioning beyond rolling, limiting their effectiveness in tightly constrained environments. While recent studies (e.g. [4]) have compared their results with state-of-the-art SLAM systems such as DLIO [9] and FAST-LIO2 [7], the field continues to evolve rapidly. Newer SLAM algorithms (e.g., FAST-LIVO2 [8]), advanced LiDARs like the MID-360 and RoboSense Airy, and modern microprocessors such as the Raspberry Pi 5—with PCIe support and Gigabit Ethernet—are pushing the boundaries of what is possible. In this context, we introduce our first prototype, the Non-actuated Sphere, which leverages the processing power of the Raspberry Pi 5 16GB RAM model. This design enables offline SLAM on a compact spherical platform, while also extending battery life through improved power efficiency and reducing overall system cost.

### *B. Spherical locomotion*

Spherical locomotion has attracted significant research interest in recent years, driven by the pursuit of optimal mobility mechanisms. Although spherical robots may appear mechanically simple, a wide variety of locomotion strategies have been developed—and continue to emerge. One of the most well-known approaches is the Internal Driving Unit (IDU), or differential drive, used in commercial robots like the Sphero Bolt+ and BB-8. Akella et al. [12] analyzed BB-8's internal wheel-driven system and demonstrated that effective control could be achieved using only two actuators. However, they highlighted a key limitation: the robot's geometry inherently restricts it to rolling motion, preventing controlled sliding and reducing effectiveness on inclined or uneven terrain.

In contrast, Zevering et al. [10] introduced L.U.N.A., a spherical robot designed for autonomous 3D mapping in lunar caves. Rather than using wheels or rods, L.U.N.A. relies on internal flywheels to generate motion via the IBCOAM method. This approach enables a compact form factor and protects internal electronics—advantages particularly well suited to harsh and remote terrain. The robot demonstrated reliable motion on soft surfaces such as sand and rubber. However, limitations remain, including vibrational instability caused by unbalanced flywheels, reduced performance on inclined low-friction surfaces, and pose estimation errors due to unsynchronized sensor data.

In a following study by Zevering et al. [13] proposed a rod-driven spherical robot, also targeting lunar cave exploration. This design uses external linear actuators to push against the environment to induce motion. While it improves adaptability to rugged terrain and sharp obstacles, it introduces new challenges, such as oscillatory behavior from fixed-speed actuators, limited effectiveness on slopes, and the need for higher-power actuation when traversing dusty or soft ground.

Beyond differential and flywheel-based designs, several researchers have explored pendulum-driven locomotion due to its mechanical simplicity, energy efficiency, and natural stability. Oevermann et al. [1], Ren et al. [2], and Kolbari et al. [3] developed spherical robots that use an internal heavy pendulum as the primary driving mechanism. While their configurations differ in terms of shell design and target applications, they share a common reliance on pendulum-based locomotion and have demonstrated robust movement across a variety of terrains.

A notable example is RoboBall [1], which features a novel soft pressurized shell and a two-degree-of-freedom internal pendulum. This robot successfully navigates gravel, grass, steep inclines, and even floats and maneuvers on water. However, the deformable shell introduces complex dynamic behaviors. These were addressed using a Linear Quadratic Regulator (LQR) for steering and a model-based proportional controller for driving. In contrast, [2] and [3] adopted PID-based stabilization strategies to enhance motion control and responsiveness. RoboBall's experiments further revealed that internal pressure and shell deformation significantly affect dynamic behavior—especially due to the presence of a "dead zone" where balance control becomes unstable during motion.

Taken together, these pendulum-based locomotion strategies highlight the value of combining mechanical simplicity with robust control to enable adaptive movement in unpredictable environments. While a variety of innovative locomotion methods have been proposed for spherical robots—including flywheel-, rod-, and pendulum-driven systems—most have been explored in isolation from modern SLAM techniques or have not been tested with active actuation. Although these designs demonstrate promising mobility across complex terrains, few have been evaluated in conjunction with advanced LiDAR-inertial odometry under real-world motion dynamics. This paper addresses this gap by introducing our second prototype—a pendulum-driven spherical robot designed to achieve both robust locomotion and accurate, real-time mapping performance within the constraints of a compact platform.

## III. Hardware Implementation

Number equations consecutively. To make your equations more compact, you may use the solidus ( / ), the exp function, or appropriate exponents. Italicize Roman symbols for quantities and variables, but not Greek symbols. Use a long dash rather than a hyphen for a minus sign. Punctuate equations with commas or periods when they are part of a sentence, as in:

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## IV. Software Implementation

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TABLE I
TABLE TYPE STYLES

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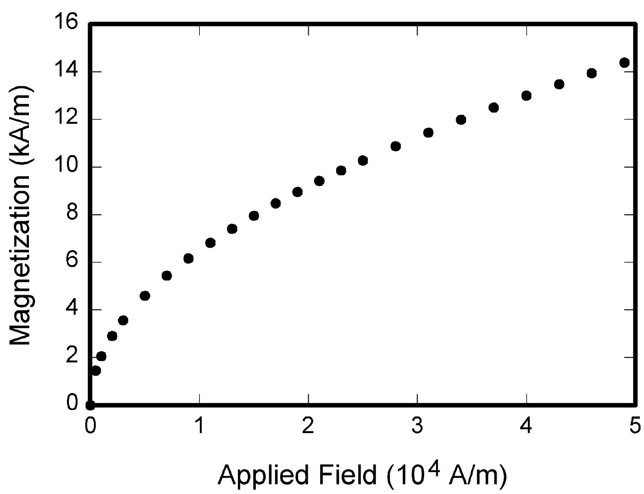


Fig. 2. Example of a figure caption.

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## ACKNOWLEDGMENT

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## REFERENCES

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For papers published in translation journals, please give the English citation first, followed by the original foreign-language citation [**?**].

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