

L.U.N.A. - A Laser-Mapping Unidirectional Navigation Actuator

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Abstract This paper proposes an autonomous, low cost approach to 3D mapping using the concept of conservation of angular momentum (COAM) as a unidirectional drive to roll a 2D laser scanner in an IMU equipped, pose-tracked spherical shell. Initially, a prototype of the robot is introduced, giving detailed insights about the hardware integration. Then, the laser scanning results as well as the COAM drive data that have been gathered using the prototype are analysed, revealing some technical problems.

1 Introduction

In today's world, autonomous robots have found their way into everyday life in a variety of ways. This includes, but isn't limited to, the vacuum cleaner that independently navigates one's living-room or mobile robots employed for exploration of areas that are too dangerous for humans. To foster new advances in the latter, specifically for underground environments, the Defense Advanced Research Projects Agency (DARPA) of the US Defense Department established the yearly "SubT" Challenge in 2017. In this challenge, teams are tasked to "Drive novel approaches and technologies to allow warfighters and first-responders to rapidly map, navigate, and search dynamic underground environments." [4] proving the demand for further research in this domain. One difficulty of this challenge is building an accurate 3D model of the environment, i.e. mapping the surroundings. The teams that participate in the DARPA challenge take advantage of high-quality hardware, such as state-of-the-art 3D laser scanners and cameras, thus making their solutions

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rather expensive. However, the demand for mapping-solutions in the low-cost sector is non-negligible. For example a set of disposable mapping devices could be used to create a 3D model of an area from different initial locations.

One such approach using a 2D laser scanner to scan 3D indoor environments has been proposed in [11]. The authors mounted a 2D laser scanner on a cylindrical structure. An operator then initiated a rolling movement by manually pushing the contraption. This enabled the scanner to sense the 3D environment with great results. However, manually pushing the scanner is not practical, especially for long scans.

Previous work was also done at the Julius-Maximilians University Würzburg [7]. The RADLER (RADial LasER scanning device) consists of a 2D laser scanner attached to the axle of a unicycle. An operator then pushes the unicycle along a requested path. The inherent rotation of the wheel then creates a radial 3D laser scanning pattern. However, this approach still requires an operator, therefore does not fulfill the autonomy requirements.

A more autonomous approach was taken in [9]. The authors mounted a rotating 2D laser-scanner on top of a [turtle-bot](#) thus removing the need of an operator. In contrast to the RADLER however, the turtle-bot does not provide an inherent rotation. Therefore an additional actuator is required to create the radial 3D scanning-pattern.

This paper builds upon the results of the RADLER and has a specific application of mapping lunar craters autonomously in mind. We propose a novel approach to low-cost 3D laser scanning using a 2D laser scanner inside a spherical robot based on conservation of angular momentum (COAM): the L.U.N.A. - sphere (Laser-mapping Unidirectional Navigation Actuator). The 2D laser scanner is fixed to the spherical structure, hence a similar situation as with the RADLER is given: the inherent rotation of the sphere creates a radial 3D scanning pattern. Using the format of a spherical robot permits the system to be designed more compact. Furthermore, an operator is no longer required given the drive implemented in the robot.

2 State of the Art

As evolution of RADLER, a hand-driven radial scanner device, a self-driving spherical approach was chosen to ensure robustness and autonomy. There have been several works in literature regarding approaches for spherical robots, of which an overview will be given in the following.

2.1 Spherical Robots

An early idea of an self-driving sphere has been introduced by J.L. Tate in 1893 who claimed the patent 508 and 558 in the U.S. for a sphere, driven by an inner moving counterweight, which got its torque from an spring. This idea of an actuator attached to an counterweight pointing to the bottom and therefore the torque being

transferred to the sphere and moving it, is still a widespread approach for spherical robots.

In [8] a basic motion control system for the BYQ-III is introduced. The BYQ-III has a mass of 25kg and a diameter of 600mm and its driving mechanism has been proposed in [3] by S.Hanxu, X.Aiping, J.Qingxuan and W.Liangqing. It contains a counterweight pendulum, four gyro actuators, providing movement for two axes and one IMU mounted on the gyros' case. There is no extra payload or sensor, nor would there be space for a centered measurement unit due to the centered counterweight. Therefore the counterweight leads to a steady movement, not relying on acceleration but on velocity of the actuators and therefore providing continuous speed.

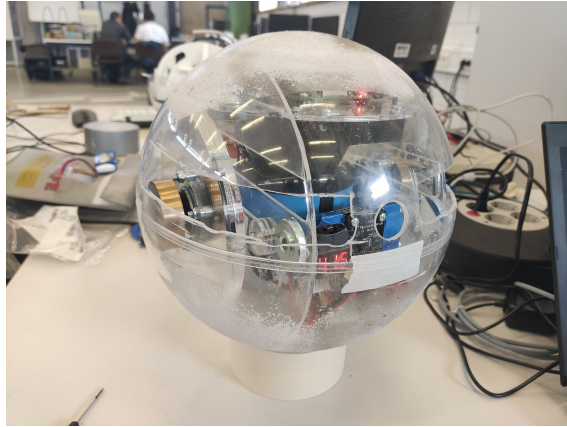
A second spherical robot with its driving mechanism relaying on inner counterweight is presented in [14]. This robot was designed for movement on a water surface and therefore has fins mounted to the shell orthogonal to the movement. Two actuators attached to the shell and the inner counterweight provide movement around one axis. In contrast to the BYQ-III a middle-centered sensor would be possible, but this would have no movement relative to the surface, as it would be part of the relatively non moving inner counterweight. It also has steady, well controllable movement. The spheres presented in [12] and [6] provide a solution for a driving system which does not rely on a moving inner counterweight but uses internal reaction wheels to provide torque. This leads to theoretically having middle-centered space available, which would be rotating with respect to the surface. However, the prototype provided by V. Muralidharan et al. shows less controllability than counterweight driven spheres. Furthermore, this robot is driven by acceleration and not velocity which leads to limited movement capabilities.

A third approach for spherical robots relies on an internal unit which drives inside the sphere. A Design and control approach is provided in [5] where a four-wheeled vehicle moves in the sphere to initiate rolling by moving the center of mass in the desired direction. This technical solution is capable of a nearly maximum size of possible payload in relation to the overall-size, but also does not provide a rotation of the sensor which would be needed for 3D laser scanning. Additionally, this provides good controllability, similar to the counterweight driven approach. It is obviously not as stable regarding external perturbations or forces, as there is no fixed connection to the shell. This would make it not suitable for missions with extreme forces and unknown starting conditions like missions involving a rocket launch or a hard landing to get to the starting point. In a worst case scenario this could lead to a start with the unit being rotated by 180 degrees and therefore not being able to bring torque to the sphere. A similar situation could occur if the sphere was stuck to the environment and therefore the inner unit would try to perform a whole revolution ("looping") inside the sphere, which would cause the car to fall on its back, i.e. a supine position.

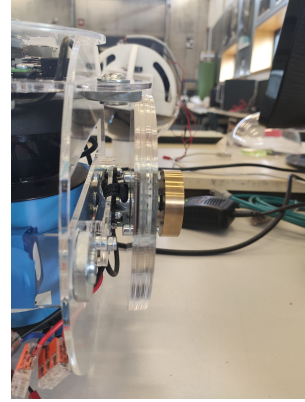
Overcoming this shortage of the inner unit just relying on gravity to apply its force to the shell, [10] introduced the approach of a rod, expanded by a spring to the maximum possible size and having a wheel on one side. The wheel generates the movement by also moving the center of mass. However, now the non-reversible supine position does not exist anymore. Even with the wheel at the top, it is still

pressed to the shell by the spring and therefore is capable of maintaining its movement. Again this approach does not provide spin of a centered placed sensor without further contraptions.

3 Technical Approach



(a) Hardware setup of the L.U.N.A sphere prototype, including notches in the shell and friction granule.



(b) IMU (beneath supporting structure) and brushless motor (above supporting structure) of the L.U.N.A sphere without shell, including flywheel mass.

Fig. 1: Hardware setup of the L.U.N.A sphere prototype, including notches in the shell and friction granule.

Figure 1a shows the final hardware setup of the robot. In order to reduce complexity with respect to the 3D-transformation calculations, the laserscanner was placed at the center of a spherical acrylic glass shell as precisely as possible. This limits the laser scanners movement to rotational movement and removes translational movement completely. With this initial setup given, the only room left for the acrylic glass structural components, batteries, boardcomputer, IMUs, motors, weights and wiring are the spaces between the scanner and the shell. Figure 1b shows one Turnigy Park480 brushless outrunner motor [2] of the COAM drive with two flywheels attached. Strong epoxy glue attaches the weights to the motor shafts and shells. As the flywheels start spinning with respect to the structural components of the sphere, the sphere itself starts spinning with respect to the ground.

3.1 Hardware Setup

Figure 1a also shows that the top and the bottom of the shell are covered in table salt, which made a good granule to increase friction to the ground in the early testing phase. Furthermore, there are notches in the front side of the shell to increase permeability for the laser. Unfortunately, the laser scanner measurements are still very much affected by blockades due to components of the sphere. Specifically, the outside shell is a strongly inhibiting factor as an object with the distance of the radius is measured at all times.

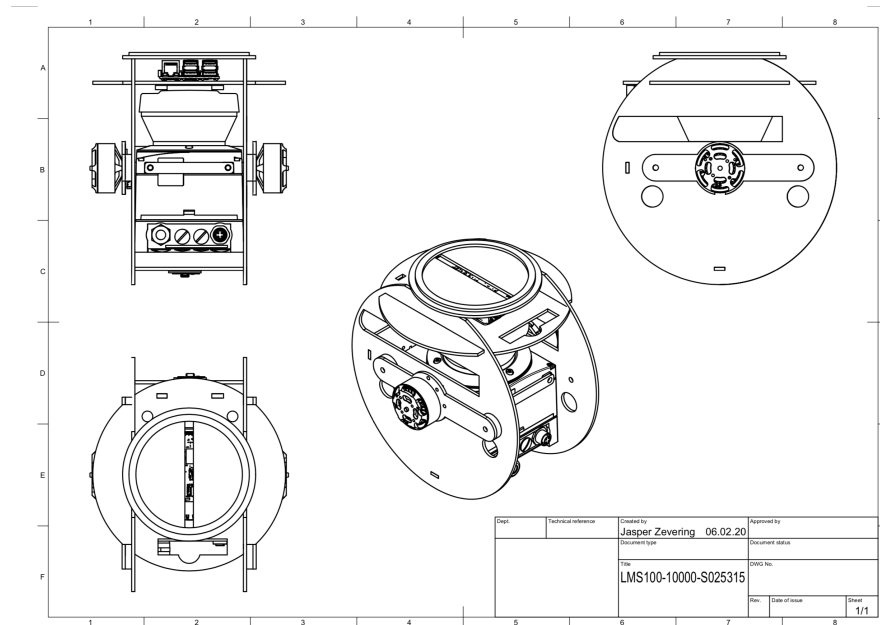


Fig. 2: Blueprint that shows the mechanical structure of the spherical robot.

Figure 2 shows a CAD blueprint of the rough interior layout of the mechanical structure of the L.U.N.A sphere, ignoring flywheels and wiring. The blueprint shows that the payload is mounted to supporting structural components which are made of acrylic glass. The raspberry pi model 3 board computer is placed on top of the laser. Above that, another supporting structure can hold additional counterweights to correct for inhomogeneous weight distribution. The battery finds its place in front of the laser scanner on another supporting structure. The two brushless motors were each placed on one side of the supporting structure with spacers that leave room for the side IMU underneath one of the motors. Two other IMUs are placed in front of and beneath the laser to ensure coverage of all axes.

3.2 Sensor Integration

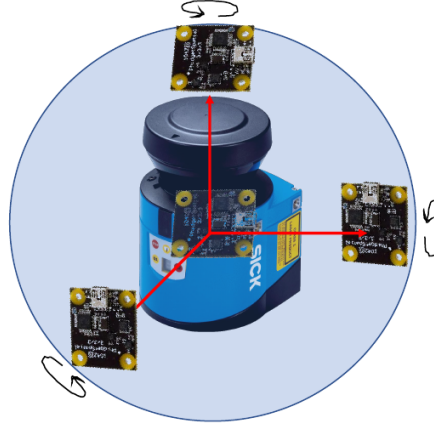


Fig. 3: Sketch that helps illustrate the combination of 3 IMUs into 1 virtual IMU that simulates being at the center of the sphere.

The sensor integration was fully implemented with the Robot Operating System (ROS) using the Ubuntu distribution [ROSberryPi](#) which contains a pre-installed ROS version running on a raspberry pi 3. Overall, three separate PhidgetsSpatial 10441B IMUs [1] were used to keep track of the sphere's pose. Figure 3 helps illustrate why three IMUs are used instead of just one. Previous prototypes have shown that transforming the data of only one non-centered IMU leads to lower quality measurements. However, combining the measurements of three IMUs, where each of which measures only the static rotation around one of their rotational axes (which also represents a rotation axis of the sphere), leads to better results. Each IMU is perpendicular to the other two, so combining the axis measurements leads to a "virtual" IMU, that simulates being an IMU that takes measurements at the center of the sphere.

The IMUs also ship with accelerometers that are used to determine the full pose of the sphere. Each IMU calculates their pose separately, using a quaternion extended Kalman filter (QEKF). However, combining those poses into one did not have any positive effect, but only made the software more resource demanding and slow. Thus only the pose of the bottom IMU's accelerometers are used to keep track of the pose.

The motors are controlled using the piGPIO library. The GPIO signals are forwarded by the pins to two ESCs that drive the motors.

Unfortunately, the brass weights were not drilled in the very center, causing an imbalance when rotating. The resulting vibrations inhibit the movement of the sphere thus a controller was implemented that measures the extent of the vibrations

using standard deviations of the IMU's axes that are not rolled over and adjusts the throttle of the motors accordingly. This was done with a simple two-point controller with hysteresis which already leads to satisfying results. Considering the translational velocity of the sphere in a controller is not possible, because the speed of the sphere is calculated by the rotational speed and therefore slippage of the sphere would break such a controller.

3.3 3D Mapping

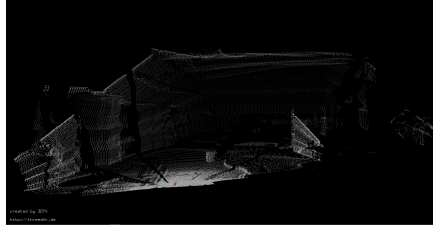
For the processing of the point cloud the 3D Toolkit (3DTK) was used. This provides multiple methods and algorithms for processing 3D point clouds, especially the 6D Simultaneous Localization And Mapping (SLAM) algorithm (see [13]). To lower the stress of the largely exhausted microcontroller, the processing of raw data was outsourced to a server-like operating pc. Therefore only the time-stamped raw data of the IMUs and laser-scanner had to be transferred and the estimation of the pose and the SLAM algorithm itself are performed external of the sphere. For this prototype the transfer was realized by using the Host-function of ROS, giving the external pc the possibility to subscribe to the topics and process them. 3DTK itself takes pairs of files, one representing the pose, one the laser scanner data, and each file named by the time-stamp with an identifier if it is scan-data or pose. With a more potent micro controller this could be performed directly onboard. Also, the use of USB-connected IMUs and ROS as transfer-mechanism of data leaves much potential for enhancement and therefore relieving the internal controller.

4 Experimental Results

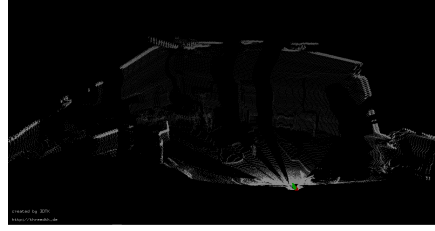
A first prototype was build using the specifications described in section 3. Using this prototype initial tests of the COAM drive and the resulting laser scanning procedure were conducted. In this section an overview over the results will be given.

4.1 3D Laser Scanning

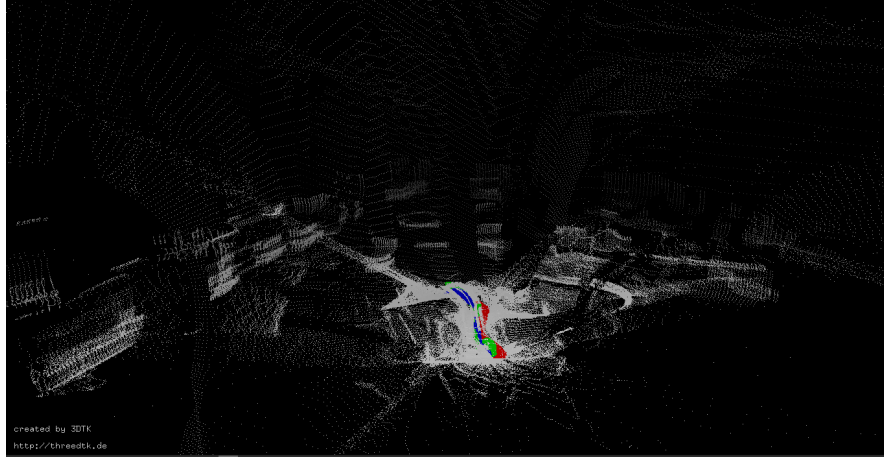
The test of the 3D Laser Scanning was carried out in 3 phases. First a semi stationary scan, moving the robot manually in a limited manner (tilting it by approximately 45°) without its exterior shell, was performed. This resulted in the point cloud in figure 4a. For the second test the same movement was used. However, this time the outside shell of the robot was present. This resulted in figure 4b. Finally a test of the overall system was conducted using the COAM-drive as motor resulting in multiple revolutions. The point cloud can be seen in figure 4c.



(a) Test with limited movement and no exterior shell.



(b) Test with limited movement but present exterior shell.



(c) Test with exterior shell and full movement (i.e. multiple revolutions).

Fig. 4: 3D Point cloud results of different test scenarios of the system.

The clearest point cloud was obtained from the first test (figure 4a). This can be contributed to the fact, that in this test the exterior shell was missing. Usually it is partially reflecting the beams of the laser scanner. Thus, the laser scanner is measuring the shell instead of the environment around it. When looking at figure 4b we can see certain lines being blocked that weren't in the previous test further showing the reflection of the laser beams by the shell. This effect is amplified as soon as the robot starts rolling. Specifically this is manifested in a large number of measurement points along the path of the robot (figure 4c).

Furthermore, the asynchrony of the pose determination sub-system and the laser scanner adds to the messiness of the point-cloud. Specifically this can be seen in figure 4c as there are points detected underneath the surface the robot was rolling on.

4.2 COAM Drive

The drive based on conservation of angular momentum was able to accelerate the L.U.N.A. sphere reliably. The angular acceleration of the whole sphere measured by the IMU - system in one test run can be seen in figure 5. It can be seen that the acceleration along the rotational axis of the flywheels rises while the accelerations along the other axes remain lower, albeit are noisy. The accelerations along the other axis can mostly be contributed to vibrations and some tilt of the robot. The vibrations are results of inexact drilling of the flywheels such that there is an imbalance. At the main test site the ground was a hard, slippery concrete floor. In such a scenario the vibrations add up and lead to slippage such that the robot no longer rolls. However, when tested on a rubber surface (a running track) the vibrations are absorbed, such that the acceleration process happens reliably.

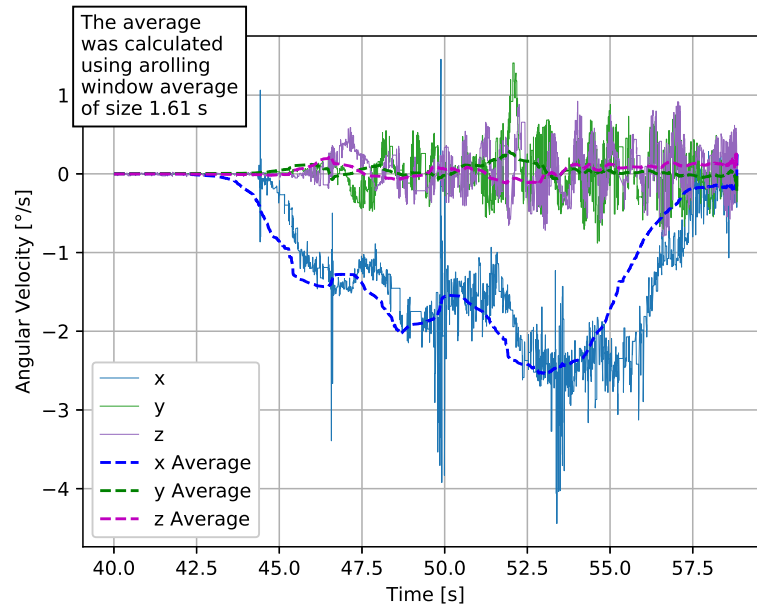


Fig. 5: Angular velocities of the L.U.N.A. - sphere during a test run. The flywheels rotate around the x-axis in positive direction. Velocities in the other direction can mostly be contributed to vibrations and tilt of the robot.

5 Conclusions

In this paper a new cost efficient approach to 3D laser scanning was proposed: The L.U.N.A. sphere. It uses a 2D laser scanner mounted inside a spherical robot and uses the inherent rotational movement to form a radial scanning pattern and hence create a 3D point cloud. The spherical robot is based on conservation of angular momentum and uses flywheels to drive the robot forward.

The prototype developed for the tests in this paper was able to move in one direction reliably on soft surfaces (such as rubber), however had difficulties with slippage on hard and slippery surfaces. In regards of 3D scanning this paper delivered a proof of concept, even though the result remain unsatisfactory as of right now. The biggest issues to overcome are reflections of the laser scanner beams by the exterior shell and synchronization issues between the IMU system and the laser scanner.

Before the application of such a robot is possible more work is required. This could include improving the field of view of the laser scanner and extending the robot to two dimensional movement control. This would then enable autonomous mapping of environments using the L.U.N.A. sphere.

Authors Note

In an attempt to abide by the [Fair-Principles](#) of open science the authors provided all code developed and further information at their [GitHub](#) page.

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