Optimal Number and Positioning of Inertial Measurement Units in Spherical Robots

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Abstract. Spherical robots are a rather niche part of robotics. Often IMUs are used for orientation determination of those robots. These IMUs are mostly placed in the center of the spherical shape, but for different subtypes of spherical robots, this is not possible due to different drive mechanism. This paper evaluates Inertial Measurement Unit (IMU) configurations for different spherical robot types in terms of orientation determination accuracy in a series of four experiments. We establish the relationship between the accuracy of orientation determination and the following aspects of IMU configurations: A) the number of IMUs, B) the distance of an IMU from the center of the sphere, C) symmetrical placement of IMUs around the sphere's center, and D) axial placement. Based on the findings of these experiments, we set up the optimal configurations for the different types of spherical robots.

Keywords: Inertial Measurement Unit, Spherical Robots, IMU-Placement

1 Introduction

Orientation estimation is crucial for successful remote missions with mobile robots. Newer missions and concepts, such as Descent And Exploration in Deep Autonomy of Lava Underground Structures (DAEDALUS) [16], deal with the idea of sending spherical robots into space. It is possible to design them holonomic or to completely seal them off from hazardous environments with the shell. They can overcome certain obstacles or recover from collisions with obstacles quickly and non-destructively. These characteristics make spherical robots suitable for tasks in space and other hazardous environments [8]. Due to required redundancy and for systems that require better performance than a single IMU provides, one approach is to use multiple IMUs and fuse them into a single high-performance artificial IMU [12, 17]. The possible placement of IMUs depends on the internal structure of the spherical robot. E.g., for the DAEDALUS sphere it

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is not possible to place the IMUs in the center, because due to the mission's concept the laser scanner is placed there. It is necessary to establish how to achieve the most accurate orientation determination for different possible IMU configurations. The same goes for different other types of spherical robots. In this paper we first introduce different subtypes of spherical robots and find suitable IMUs configurations for them.

2 Related Work

2.1 Characteristics of Multi Inertial Sensor Systems

Skog et al. [17] give a comprehensive overview of the basic characteristics of Multi Inertial Sensor and Multi Inertial Measurement Unit (MIMU) systems and the corresponding gains. In summary, the fundamental properties of MIMU systems are Stochastic Error Diversity, Component Redundancy and Diversity, Spatial Diversity, and Temporal Diversity. The focus in this paper is on the benefits provided by stochastic error and spatial diversity.

Stochastic Error Diversity Combining independent measurements suppresses independent stochastic errors, such as distortion and noise [17]. Guerrier [10] shows, that for n independent measurements of equal variance (σ_n^2) the theoretical noise reduction $\sigma_{\hat{x}}$ represents the maximum improvement in navigation performance, with $\sigma_{\hat{x}} = \sigma_{xi}/\sqrt{n}$. This relation applies to any sensor configuration. [7] also establishes this correlation between n (the number of IMUs used) and noise reduction. Their work shows that after $n = 10$, the accuracy improvement is no longer profitable. Ludwig [12] evaluates different numbers of sensor configurations of a Magnetic and IMU sensor array using a simulation environment. The evaluation measure employed is the Root Mean Square Error (RMSE) based on Euler angles determined by the Madgwick Filter versus ground truth. The results also show an exponential downward trend in the RMSE values. Greenheck [9] develops and demonstrates an IMU cluster configuration for a 1U CubeSat. The results generally approximate the predicted square root of n of the performance improvement for the RMSE.

Spatial Diversity Pesja [15] developed the first theory for obtaining an optimal configuration regarding the placement of any number of sensors in 1974. Optimal configurations in information space take the form of a sphere, i.e. an equal amount of information on each axis. Further research of [18] using the information filter method shows that for n sensors with equal variance the optimal configuration in the two-dimensional case conforms to a homogeneous distribution on a unit circle (regular polygon). In the three-dimensional case, on the other hand, there is no unique solution, since the optimal configuration, despite having a unique shape, can have an arbitrary orientation. Generally, regular polyhedra is the optimal configuration for 4, 6, 8, 12, and 20 sensors. Guerrier [10] uses the partial redundancy method, evaluates the controllability of each sensor, and gets in general similar results as the information filter approach. Further this method shows that for triaxial IMUs, the relative sensor alignment is irrelevant to the optimality of the system. Therefore he recommends an orthogonal arrangement, which is usually the simplest configuration.

According to Zevering [22] one non-centered IMU leads to lower quality measurements. Therefore they combine the data of three non-centered IMUs, where each IMU only measures the static rotation along one of the rotational axes. This method leads to less noise in the overall angular velocity measurements.

In the case of sensors, however, it is necessary to distinguish between location-dependent (accelerometers and magnetometers) and location-independent (gyroscopes) sensors [5]. Zappa [20] uses this fact to obtain the complete acceleration state of a rigid body with twelve accelerometers under the following conditions: division of the accelerometers into three groups, same orientation for all accelerometers of each group, different and linearly independent orientation of the three groups, and non-coplanar accelerometers within each group.

2.2 IMU-based pose-estimation for spherical robots

The orientation determination in this paper is based on pose determination using IMUs of [23]. This pose determination method works for any spherical robot with IMUs that moves based on rotation. This method uses a combination of the Madgwick and the Complementary Filter. It has low jitter to keep the world measurements constant at standstill and also avoids exponentially growing errors in position estimation. The prerequisite is that the IMUs rotate along with at least the shell of the robot.

3 Spherical Robot Types

To obtain optimal configurations for the different spherical robot types, we present the different types in terms of their structure and constraints for IMU placement. Spherical robots are distinguished by their methods of propulsion and are divided into two main groups. Figure 1 shows the group that uses barycenter offset for motion. This group includes the following types:

Pendulum Based: pendulum including a pendulum body attached to a horizontal axis that passes through the sphere's center. Rotation and shifting of the pendulum leads to movement of the shell. [6, 8]
IMU Placement: in the shell or on the rotation axis outside the pendulum's shift

Internal Drive Unit (IDU): wheel based concept with an internal vehicle, which changes the position of the center of mass of the overall system. Three subtypes: Hamster ball, Spring-loaded IDU, and Universal wheel. [6, 8]
IMU Placement: only in the shell for the use of Zevering's filter

Shifting Masses: shafts with movable weights attached to them connect the central mass to the shell. Movement of the robot by redistribution of the masses along the shafts. [13, 14]
IMU Placement: in the shell, or inside the sphere outside the masses' reach.

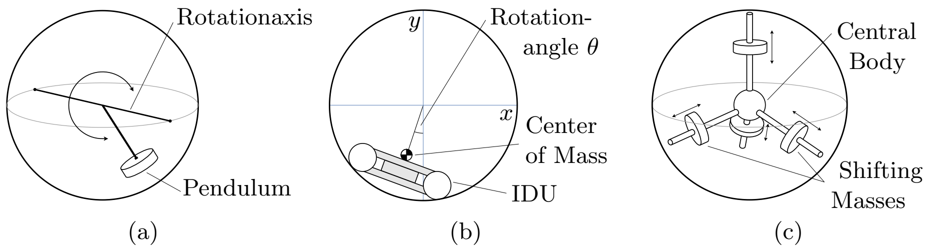


Fig. 1: Overview of spherical robot types using barycenter offset for locomotion. (a) Spherical robot (black circle) with pendulum mechanism. Schematic representation according to [6, 8] from the slanted view. (b) Spherical robot (black circle) with IDU, here: hamster ball according to [1] including the Base Coordinate System (BCS). (c) Concept of a spherical robot (black circle) using the shifting masses (cylinders with arrows) principle according to [14].

Besides the group that uses the displacement of the barycenter for locomotion, there are three other types. Figure 2 shows for each of those types an example.

Shell Transformation: deformation of the outer body to move the robot [6]. Examples: Artusi [2], and Wait [19].
IMU Placement: no placement in shell, inside placement depends entirely on the internal structure of the robot and varies with the specific design and shell forming approach.

Reaction Wheels: Control of the movement of the robot by rotating a large flywheel quickly about an axis [6]. Examples: Gyrover, presented in [3, 4], and the design by Joshi [11].
IMU Placement: in the shell, or inside, which depends on the internal structure and must be chosen for each individual robot.

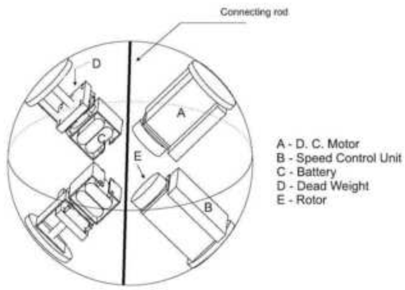
Rod-Driven Locomotion: supports connect two similar disks containing the rod stars and a slightly larger center disk. Movement of the robot by pushing or by using leverage. [21]
IMU Placement: in the center, as well as in the shell, onto the middle disk or between the disks.

4 Approach

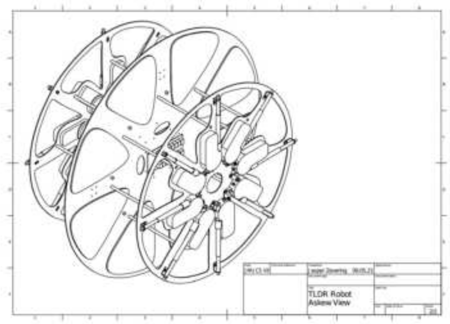
Regarding the quantity of IMUs, we expect an exponential decreasing trend of the RMSE based on [7,9,10,12]. Depending on the number of IMUs n, we assume the RMSE will follow the form of

$$RMSE \sim \frac{1}{\sqrt{n}}\,. \tag{1}$$

Since we use gyroscopes and accelerometers in the filter the orientation determination depends on the placement of the IMUs according to [5]. We presume



(a)



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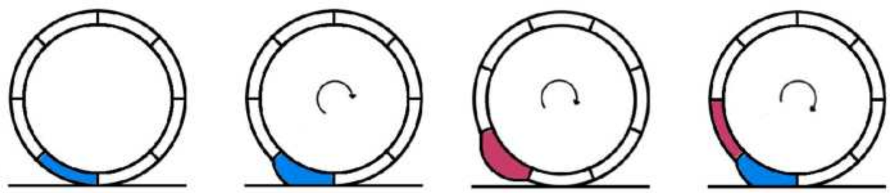


(c)

Fig. 2: Overview of spherical robot types using different approaches for locomotion. (a) Internal structure of Joshi's spherical robot using reaction wheels [11]. (b) Blueprint of the rod-driven robot without the spherical shell [21]. (c) Cross-section of a shell transforming spherical robot (black circle) with pressurized air bladders in motion by Wait [19]. Blue: inflating. Red: deflating.

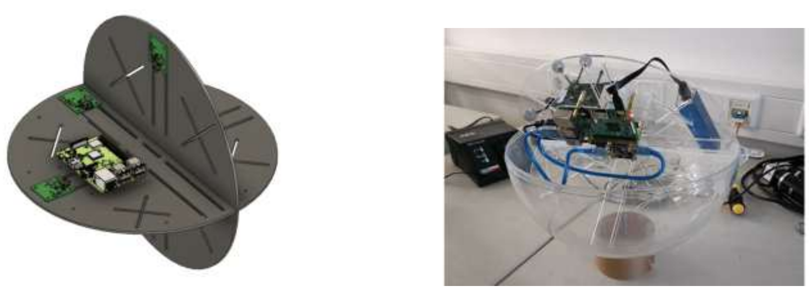
that an IMU in the center of the sphere determines the orientation more accurately than an IMU placed off center. This assumption is based on the fact that the accelerometers in the center of the sphere do not experience significant height differences when the sphere is moving. Thus, they do not measure accelerations other than the acceleration from the motion of the entire sphere.

When placing the IMUs, we use mainly equal distances between the IMUs, since optimal configurations have the shape of polygons or polyhedra according to [18]. The relative orientation of the individual IMUs is irrelevant for the optimality of the system as stated by [10]. We locate the sensors only on the rotation axes, ergo an orthogonal arrangement as recommended by [10], to limit the complexity and the extent of this work. According to [20], it is possible to measure the angular velocity of the body using four non-coplanar IMUs. We consider the configuration of four non-coplanar IMUs to be worth an experiment.

Specific Approach For pendulum based robots, spherical robots with shifting masses, and rod-driven robots it is possible to set the distance of the IMUs, even if limited, from the center of the sphere. It is therefore important to determine the accuracy of the orientation determination as a function of the distance of an IMU from the sphere's center. Regardless of the distance, it is possible to mount two IMUs on opposite sides of the center of the sphere on the same rotation axis. Thus, an experiment that determines the symmetry in the placement of the IMUs on a single axis is necessary. For those types where the placement of the IMUs in the shell is possible, e.g., robots with an IDU, we set up the following placement options for the IMUs, taking into account the limitations already established. Since according to [22] only one non-centered IMU leads to lower quality measurements, we want to determine whether three IMUs, one on each axis of rotation, give similar accurate orientation estimations as three IMUs located in the center. If the symmetrical placement of the sensors proves advantageous, we want to establish whether an arrangement of six IMUs (two on each axis on opposite sides of the sphere's center) is more accurate than all of them in the center. For rod-driven robots, a configuration with one IMU in the center of the sphere, as well as one on each axis in definable distance from the center is possible. For robots that use reaction wheels or shell transformation it is necessary to place the sensors specifically for each individual robot.

5 Experiments and Evaluation

For the experiments we use six PhidgetSpatial Precision 3/3/3 High Resolution 1044_1 IMUs, the filter presented in [23], and an Optitrack V120 Trio 330694 for ground truth measurements. Figure 3 shows the mounting for the IMUs. For more statistical robustness we conduct three experiments for each configuration (Roll, Pitch and a combination of Roll and Pitch movements). To compare the individual configurations, we calculate the total RMSE for each configuration by combining the RMSEs of the three experiments performed. We calculate the relative error, here called improvement, between the configurations to compare them. According to this definition a negative improvement means smaller RMSE. We define a significant improvement as $|\text{IMP}| > 5\,\%$. In order to obtain comparable results for each experiment, each individual experiment is performed in one session.



(a) (b)

Fig. 3: Mounting for the IMUs. (a) Computer-Aided Design (CAD) Model with exemplary mounting of three IMUs and the Raspberry Pi. (b) Picture of the real setup with three centered IMUs, the Raspberry Pi and a 5 V powerbank.

5.1 Experiment A

In our first experiment we review the relationship between the number of IMUs and the RMSE, refer to equation 1. We compare the following number of IMUs n in the center of the sphere: $n = 1, 2, ... 6$ (A1 - A6).

Results Adding more IMUs in the sphere's center significantly improves the orientation determination accuracy. By taking the mean of the measurements to combine the measurements of all IMUs we average the independent stochastic error out, refer to [17]. We detect that the difference between the improvements compared to one IMU in the center decreases with increasing number of IMUs. Figure 4 visualizes the RMSEs plotted against the number of IMUs. As expected, we observe that exponential downward trend, refer to equation 1. We observe this exponential downward of the RMSE values also in the relative improvement values for an increasing numbers of sensors. To compare the configurations more closely, we calculate for each configuration the improvement in reference to the previous configuration with one IMU less in the center of the sphere. For six IMUs in the center of the sphere, we have only an improvement of 2.1099 % in comparison with five IMUs in the center of the sphere. Ergo, for a number of five IMUs and above, the improvement in the accuracy of the orientation determination is no longer significant. Thus, the application of more than five IMUs is not profitable for the accuracy of orientation determination.

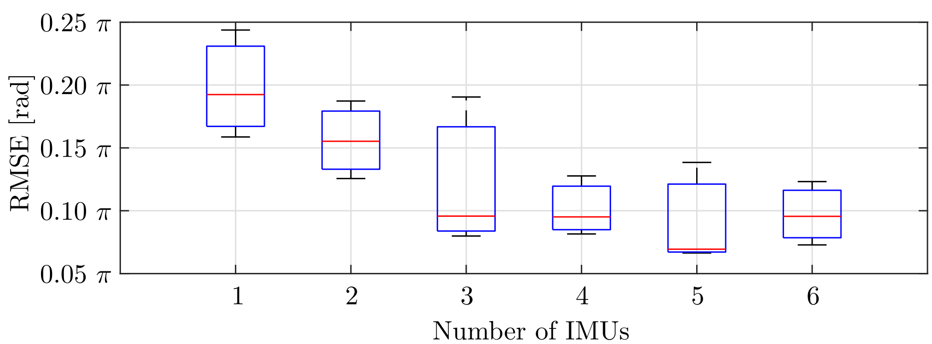


Fig. 4: End results of Experiment A. Merged RMSE [rad] for each configuration plotted against the number of IMUs.

5.2 Experiment B

The second experiment serves to determine the dependency of the orientation determination accuracy on the distance of the IMU from the center of the sphere. For this purpose, starting from the center of the sphere, we move one IMU gradually outward along a chosen axis by a predefined distance d to the edge of the sphere. We compare the following configurations: (B1) One IMU in the center of the sphere, (B2) One IMU at $d = 4.170\,\text{cm}$, (B3) One IMU at $d = 7.859\,\text{cm}$, (B4) One IMU at the edge of the sphere at $d = 11.548\,\text{cm}$.

Results From the gathered data, we conclude that one IMU placed in the sphere's center is significantly better than one placed further out regarding the orientation determination accuracy. This confirms our previous presumption in Section 4. The results from configuration B2 and configuration B4 are nearly identical. Configuration B3 shows a slightly larger RMSE. The improvement of configuration B3 in reference to B2 or B4 (here we choose B2) is 0.5095 %. Thus, the difference between the orientation determination accuracy for configuration B3 and B2 or B4 is insignificant. Figure 5 visualizes the RMSEs plotted against the distance d of the IMU from the center of the sphere. When we place an IMU off centered, the distance to the sphere's center seems to have no effect on the accuracy of the orientation determination.

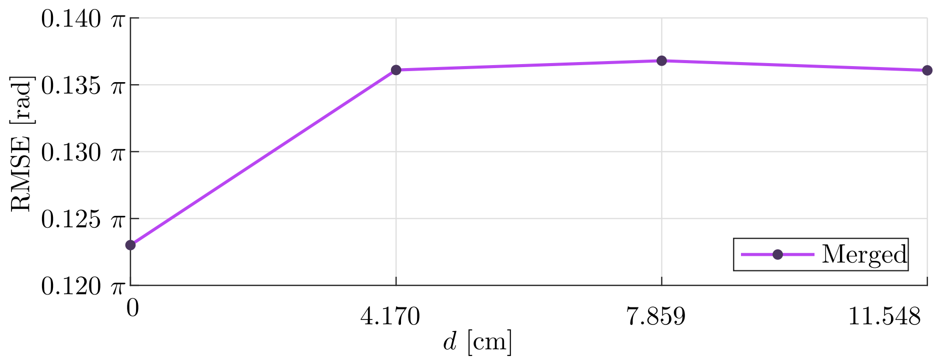


Fig. 5: End results of Experiment B. Merged RMSE [rad] for each configuration plotted against the distance d from the center of the sphere.

5.3 Experiment C

This experiment evaluates how the symmetry in the placement of IMUs affects the orientation determination accuracy. We compare two configurations: (C1) both IMUs on the same side of the sphere's center at a predefined distance versus (C2) two IMUs on opposite sides of the center of the sphere with the same distance. For the distance between IMUs and the center of the sphere, we refer to the result of Experiment B. Since for $d > 0$ the distance does not seem to have any effect on the accuracy of the orientation determination, we choose the minimum possible distance between the center of the sphere and our IMUs ($d = 4.170\,\text{cm}$).

Results Table 1 lists the merged RMSEs and the relative improvements. The improvement of configuration C2 in reference to configuration C1 is with 1.3965 % insignificant. From the results, we see that symmetrically placing two IMUs around the sphere's center on one axis provides an as accurate orientation as placing two IMUs on the same side of the sphere's center on the axis.

Table 1: Results of Experiment C. Merged RMSE for each configuration and relative improvement compared to the first experiment (here C1).

Experiment	C1	C2
RMSE [rad]	0.3510	0.3559
Improvement [%]	–	1.3965

5.4 Experiment D

In the last experiment we determine the influence of axial placement of the IMUs on the orientation determination accuracy. We take the result of Experiment A into account for the choosing the number of IMUs. We set the number of IMUs to three to avoid a possible advantage for this configuration by using more IMUs. In Experiment C, we show that a symmetrical placement of IMUs is not beneficial for orientation determination. Therefore, we do not perform experiments for the following configurations: two IMUs on each axis, and six IMUs in the sphere's center. We compare the following configurations: (D1) Three IMUs in the center of the sphere, (D2) Three IMUs each on one rotational axis, (D3) One IMU in the sphere's center and three IMUs each on one rotational axis.

Results Table 2 lists the merged RMSEs and the relative improvements. The most accurate configuration regarding orientation determination is D1 (three IMUs in the center of the sphere), followed by the configuration D3 (One IMU in the sphere's center and three IMUs each on one rotational axis). The configuration D2 with one IMU on each rotational axis gives the least accurate orientation. If we compare D2 and D3 directly, we get an improvement of -8.46 % with D2 being the reference configuration. Adding an additional IMU in the sphere's center improves the orientation determination accuracy significantly. Against three IMUs in the center of the sphere, however, D3 is not more accurate despite the one more IMU, since the three IMUs placed on the outside provide worse results for the orientation determination accuracy.

Table 2: Results of Experiment D. Merged RMSE for each configuration and relative improvement compared to the first experiment (here D1).

Experiment	D1	D2	D3
RMSE [rad]	0.3361	0.4082	0.3736
Improvement [%]	–	21.4251	11.1554

5.5 Evaluation

For pendulum based robots we recommend placing five IMUs in the shell anywhere on the rotational axes and/or on the pendulum's axis, since the distance between an off centered IMU and the center of the sphere, as well as symmetrical placement of the IMUs, does not affect the orientation determination accuracy. If the robot needs to be well balanced, we recommend using six IMUs, because six IMUs are better to evenly distribute than five IMUs and the mechanical as well as the electrical overhead by using one more IMU is low. This approach for a well balanced robot applies for all following types, where we recommend using five off centered IMUs. For spherical robots with an IDU we suggest placing five IMUs on the rotational axes in the sphere's shell. The distribution of the IMUs on the rotational axes does not matter. For robots with shifting masses we recommend placing five IMUs anywhere on the rotational axes outside the shifting masses' reach, which is most likely in the shell. For rod-driven robots including DAEDALUS, it is best to place five IMUs in the sphere's center, because the orientation determination of an IMU is most accurate when we place them in the center of the sphere. The same approach applies for robots using reaction wheels or shell transformation, where an individual placement for each specific robot is necessary. For DAEDALUS it is not possible to place the IMUs in the center of the sphere due to the laser scanner. Therefore, the next best configuration for them is to place five IMUs off centered anywhere along the rotational axes.

6 Conclusion

In this paper, we have studied the effect of different IMU configurations in terms of quantity and arrangement on the accuracy of orientation estimation. We performed four experiments to establish how the following aspects affect this accuracy: A) number of IMUs, B) distance of an IMU from the sphere's center, C) symmetrical placement of IMUs, and D) axial placement compared to centered placement of the IMUs. We showed that the application of more than five IMUs is not profitable for the accuracy of orientation determination. An off centered IMU gives less accurate orientations than an IMU at the center of the sphere. However, the distance to the sphere's center for off centered IMUs seems to have no effect on the accuracy of the orientation determination. Symmetrical placement of two IMUs around the sphere's center does not provide more accurate orientations than an asymmetrical placement. Axial placement of three IMUs gives less accurate orientations compared to centered placement of the IMUs. From this we derived configurations for the different spherical robot types in section 5.5. The results mostly fit with the empirical expected behavior, e.g., more IMUs and smaller distance to the center lead to higher accuracy. Still, the reference value (RMSE) is significantly high for all performed experiments.

Needless to say, a lot of work remains to be done. Further research needs to establish the exact connection between the distance of an off centered IMU and the center of the sphere and the orientation determination accuracy, with the help of a more precise ground truth. Further research may also include the usage of different IMUs to elaborate the possible advantages due to temporal diversity and redundancy for Fault Detection, Isolation, and Recovery (FDIR). It may also use a theoretical model and simulations to test more configurations. A much bigger task will be to implement the findings on the number and placement of IMUs of this work on the respective real spherical robots and to perform real world tests with all subtypes of spherical robots. With the knowledge gained from this with regard to practicability, we will be able to develop more generally optimal configurations, which then include other criteria besides RMSE, such as practicability, cost, etc.

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