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Tether-Based Localisation System for Underwater Robots

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***Abstract* — Tank-inspection robotic crawlers often rely on localisation techniques such as dead reckoning to survey walls and surfaces. However, the robot position can drift over time when using these techniques, which therefore require precise calibration. This paper presents a novel tether-based system providing a real-time localisation reference tool to help calibrate and understand prevalent localisation technologies, inside uncluttered tanks. The assessed localisation technologies can subsequently be used in cluttered and complex operational tanks. The developed system relies on a mechanical connection between the tank edge and the robotic crawler and is composed of two distinct units. The first unit is the tether orienting platform clamped onto the tank edge and guiding a tether coming out of a draw-wire position sensor. The second unit is the crawler platform mounted on top of the robotic crawler and holding the tip of the tether, while allowing the robot to move freely. The performance of the system is assessed by determining the accuracy on the 3D position of the robot and the accuracy on its 2D heading, over a 1m x 1m area. The positional accuracy with 90% confidence interval is ±39mm and the heading accuracy with 95% confidence interval is ±4.8°.**

Tethered Robotics – Localisation System – Tank Inspection – Robotic Crawler – Forward Kinematics.

I. INTRODUCTION

A. Background

Real-time localisation is crucial for remote controlled systems as well as autonomous systems especially in cluttered [1], hazardous [2], and unknown environments [3]. On the one hand, it enables the operator to remotely track the location of the robot, on the other hand, it enables autonomous systems to constantly receive an estimation of their position and orientation and take actions accordingly. Localisation is also important for survey or inspection tasks, which rely on the mapping and understanding of the environment, to correlate observations from the robot with their precise localisation. Thus, developing accurate and affordable localisation technologies and algorithms is vital for the robotic field related to (underwater) exploration.

B. Literature review

State-of-the-art localisation systems for underwater robots include sonar-based and tether-based technologies. The sonar-based technology originates from the Neptune system (North-East Pacific Time-Series Undersea Networked Experiments), an underwater robot used to remotely inspect aboveground storage tanks [4]. The next generation of its acoustic localisation system (Sonic High Accuracy Ranging and Positioning System II known as SHARPS II) relies on high-frequency, spread-spectrum techniques to produce precise time-of-flight range measurement with sub-centimetre scale resolution [5].

The SHARPS technology is similar to baseline acoustic positioning systems which include long baseline (LBL), short baseline (SBL) and ultra-short baseline (USBL) systems. LBL systems measure ranges between a shipboard hydrophone and two or more transponders mounted at the bottom of the ocean [6]. SBL systems require three or more shipboard hydrophones receiving data from a single beacon at the bottom of the ocean. USBL systems can provide accurate measurements with a single multielement shipboard hydrophone and a single beacon on the ocean bottom. Each baseline system can be used for a specific application and environment. According to [5], [7], and [8], their scale resolution is on the order of metres and their heading accuracy is less than a degree.

Sonar-based technologies are accurate but expensive to install and maintain. In contrast, tether-based technologies are relatively low-cost for underwater real-time localisation. The reference for tether-based underwater localisation systems is the Smart Tether, patented by US company KCF Technologies in 2013 [9]. This tether is composed of sensors embedded within a portion of a flexible tether. Knowing the spacing between each sensor along the cable, and using the 2D catenary curve equations consecutively, the position of each sensor can be determined in the 3D space, as explained in [9]. The product is still being sold in 2022 by VideoRay and shows good performance for small/medium ranges (40m) with a scale resolution on the order of metres and a heading accuracy of less than a degree.

The tether-based technology is more practical for punctual underwater investigations, and although a bit less precise, it is more affordable than the LBL. Improved tether-based technologies relying on fibre-optic shape sensing (FOSS) [10] are more accurate. These technologies can involve the use of Fibre Bragg gratings (FBG) [11], to provide discrete bending parameters of the tether, and combined with 3D curve equations, help derive the shape of the tether [12]. Although they are light, accurate, geometrically versatile, they lead to complex implementation in harsh environments (e.g. water environment) where they are fragile, sensitive and intended at small-scale use.

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Tether-based technologies can also be found in the form of tether length and orientation determination systems rather than tether deformation systems. The leading device able to determine the tether length is called a draw-wire position sensor, or cable-extension transducer system (CET), presented in [13]. Pulleys are combined with the CET and relying on a pan-tilt mechanism to ensure that the cables come out with the same orientation as the robot. A triangulation algorithm is then used to compute the position of a second robot attached to a master robot, using a paired CET system. Another tether-based technology used to evaluate the orientation of an object in 3 dimensions is presented in [14]. The position control concept includes a cable-suspended platform, encoder systems (force sensors, potentiometers) and cable length measurement systems. The performance of a custom combined position and orientation determination system can reach a scale resolution on the order of millimetres for a range of around 10m and a heading accuracy of less than a degree.

Alternative underwater localisation technologies exist but face significant drawbacks such as GPS systems being unreliable under water and camera-based systems not being performant in poorly lit environments.

C. *Problem definition*

Nautilus bathyscaphic robot is a tethered underwater robotic crawler funded by Innovate UK for storage tank inspection, initially relying on dead reckoning for localisation. Over long distances or long operating time, the position error with dead reckoning method increases gradually. For instance, a bias error in acceleration becomes linear in velocity and quadratic in position. A solution to alleviate the error drift is to rely on another localisation reference or calibration system to update the position and orientation of the robot after a specific duration, or to compensate the error increase thanks to a thorough calibration process.

The aim of the paper is to design and create a system for calibrating and understanding dead reckoning localisation estimation errors. The system must provide accurate 3D position and 2D heading orientation estimations of the centre of mass of the robotic crawler in real-time. The positional accuracy of the prototype must achieve ±20cm over a 5m range (diameter of the test tank) and its orientation accuracy must achieve at least ±5° to provide exploitable data for the localisation technologies to be correctly calibrated. The uncertainties provided are given according to a 90-95% confidence interval.

II. METHODOLOGY

A. *Theoretical localisation estimation*

In order to get a theoretical estimation of the positional and orientation accuracy of the proposed system, an algorithm was created. MATLAB was selected to handle complex matrix calculations. Relying on a forward kinematics approach to derive the position of the robot from random "joint configurations" (representing configurations of the system), coupled with error propagation formulas to take into account the individual error of the various sensors, the algorithm averaged the estimated standard deviation of the position and orientation error for 1000 random realistic configurations. A 1m-long wire was considered for the theoretical model to serve as reference for the experiment.

B. *Experimental localisation estimation*

To assess the positional and orientation accuracy of the assembled innovative localisation system, the OptiTrack by NaturalPoint Inc was utilised. The OptiTrack provides precise 3D tracking of any entity thanks to physical markers, high-end cameras, and the Motive software suite.

Three cameras were selected to monitor a 1m x 1m area representing the bottom of the tank. The setup, in the aerial environment to ensure good OptiTrack performance, is shown in Fig. 1. Once calibrated, the OptiTrack can produce positional error less than 0.3mm and rotational error less than 0.05°, according to the manufacturer.

Five motion capture markers have been placed directly onto the robotic crawler to determine the position of its centre of mass in 3D in real-time, as well as the heading orientation of the rigid body. Using five markers instead of three ensures that at least three markers are visible at all times by the OptiTrack and that the measurements are uninterrupted if one or two markers are hidden by the body, for instance one marker is hidden in Fig. 1. Four markers have also been placed onto the tank bracket holding the innovative system to set the origin of the work area and define a reference frame for the robot motion.

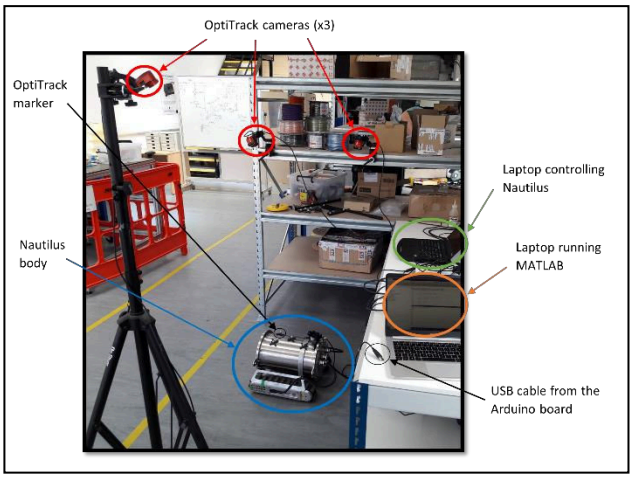

Figure 1. OptiTrack cameras initial setup

To compute the estimated position and orientation of the centre of mass of Nautilus in real-time from sensor measurements, an Arduino MEGA 2560 has been selected for its number of interrupt pins, performant Analog-to-Digital converter (>10-bit resolution), small size (maximum 100 mm * 100 mm * 50mm) and affordable price. The MATLAB localisation estimation program used in the simulation phase has been converted into an Arduino program to make use of real-time sensor data and has been run on a laptop (Huawei Matebook D14). Nautilus was driven around the free space, while the Arduino board processed the data coming from the

sensors and sent the position and orientation estimation of the crawler to MATLAB main program (3Hz updates).

In parallel, Motive software was recording, via the OptiTrack cameras, the position and orientation of Nautilus centre of mass in real-time. The OptiTrack data was sent to MATLAB with a user-defined delay every time the Arduino program collected data from system sensors. This way, measurements from different sources were taken at the same time i.e. representing the same position and orientation of the robot while it was moving. The MATLAB program then gathered the position and orientation estimations into a unique table. The data acquisition structure is shown in Fig. 2.

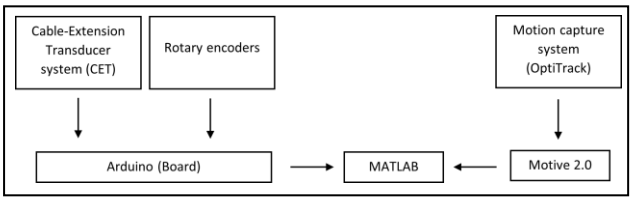

Figure 2. Real-time data acquisition structure for system testing

During the data analysis phase, outliers representing OptiTrack data miss (less than 3 visible markers during capture time) or a sudden shift in values (external disturbances such as lighting), were manually removed from the table.

For the experiment, Nautilus was driven randomly across its free 2-dimensional space, at a specific floor height, for 5 minutes, which corresponds to 800 different configurations recorded after outlier removal.

III. Results and Discussion

A. Technical details

To comply with the main requirements from the calibration project (uncluttered test tank with a height of 1m, a diameter of 5m and a flat bottom), and according to the literature review, the most suited technology for the localisation system is a tether-based technology. A mechanical connection between the tank edge and the robotic crawler provides various benefits such as: satisfying accuracy, easy setup, versatility, affordability.

In order to evaluate the position and orientation of the robot inside the tank, the system architecture presented in Fig. 3 has been adopted.

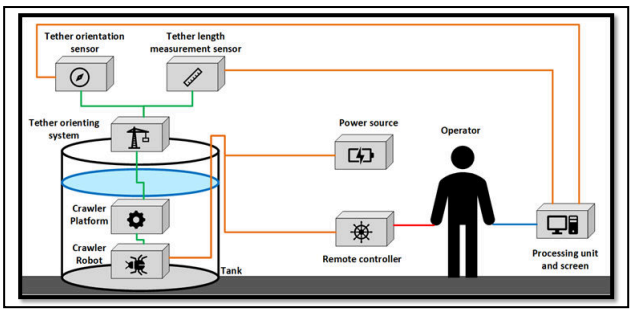

Figure 3. Subsystem architecture and interfaces

The localisation problem has been solved with a single-wire localisation approach inspired from tethered simultaneous localisation and mapping (TSLAM) [15], relying on the determination of 2 angles (horizontal and vertical rotations) and tether length, as shown in Fig. 4

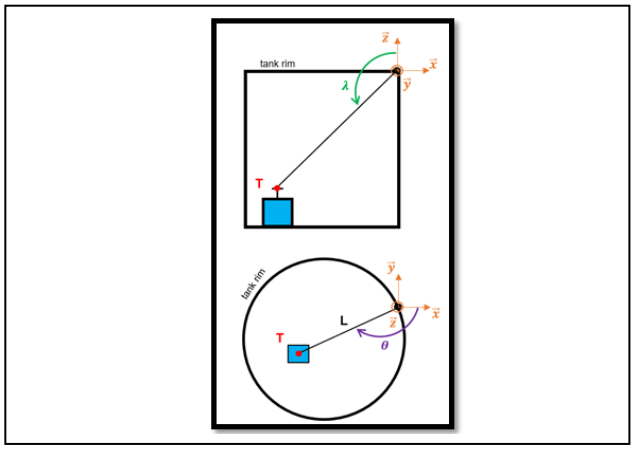

Figure 4. Side and top view for the single-wire localisation approach

The innovative system used to determine the 3D position and 2D orientation of the underwater crawler can be divided into two subsystems or units.

The first subsystem is a rotating draw-wire platform, placed on top of a tank attachment entity, which includes a deflection pulley and wire-guiding system to ensure that the desired angles are precisely measured and that the mechanical disturbances are minimised. The angles are parametrised by θ and λ shown in Fig. 4.

The second subsystem is the crawler attachment used to connect the wire to the robot while providing the heading angle of the rigid body (angle not represented in Fig. 4).

The assembled subsystems, combined with 1 draw-wire position sensor (AK Industries CD50 1000-R01K-L15-K01-OP-IX), 3 rotary encoders (Wisamic encoder LPD3806-600BM-G5-24C), is presented in Fig. 6.

B. Theoretical results

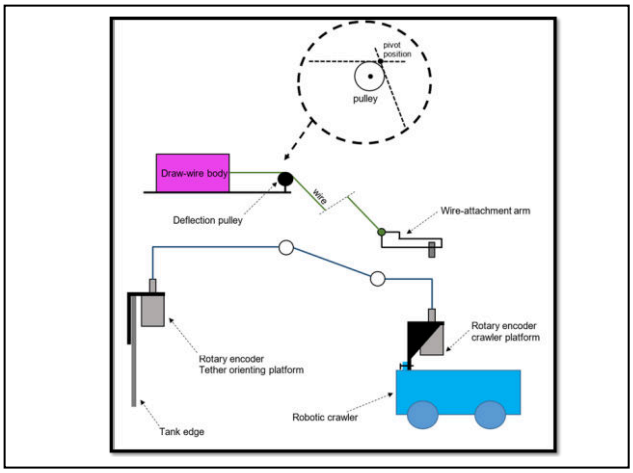

Figure 5. Forward kinematics explanatory model of the system

The theoretical model has been approximated with the model shown in Fig. 5 and used to derive the Denavit-Hartenberg (D-H) parameters of the forward kinematics model.

To determine the accuracy of the system and compare it to other existing systems, the standard deviation is calculated using the error propagation rules. The standard deviation for each coordinate of the position of the crawler (σ_X, σ_Y, σ_Z), as well as the standard deviation for the heading angle of the crawler ($\sigma_{Heading}$), are calculated from the standard deviations of the measuring devices and production devices (3D printing machine).

The error proparagation formula is calculated for any variable Z which depends on other variables according to the function Z = f(A,B,C). The uncertainty on Z (ΔZ) can be expressed with the uncertainties on the other variables ΔA, ΔB, ΔC, as shown in (1).

$$\Delta Z^2 = \left(\frac{\partial f(A,B,C)}{\partial A}\Delta A\right)^2 + \left(\frac{\partial f(A,B,C)}{\partial B}\Delta B\right)^2 + \left(\frac{\partial f(A,B,C)}{\partial C}\Delta C\right)^2 \quad (1)$$

ΔZ represents the uncertainty with 68% confidence interval. To obtain an estimation with 95% confidence interval, ΔZ has to be doubled: $\Delta Z(95\%) = 2\times\Delta Z(68\%)$.

Uncertainties with 68% confidence interval can be determined from different sources: the manufacturer providing the resolution or accuracy of the device, a single measurement with the device (uncertainty type B) or a sample study (uncertainty type A).

The propagated errors for the variables of interest (position coordinates and heading angle) can be derived from the uncertainties with 68% confidence interval for each device used and from formula (1). The values are shown in Table II.

According to [16], the Mean Radial Spherical Error (MRSE) can be calculated to determine the 3D accuracy of the position. It represents the radius of sphere centred at the true position, containing the position estimate in 3D with probability of 61%. To obtain the radius of sphere centred at the true position, containing the position estimate in 3D with probability of 90%, the formula shown in (2) is used.

$$MRSE(90\%) = 0.833 \times (\sigma_X + \sigma_Y + \sigma_Z) \quad (2)$$

Uncertainties with 90-95% confidence interval are subsequently calculated and shown in Table I.

TABLE I. POSITION AND HEADING UNCERTAINTY

Uncertainty	*Value*
MRSE(90%)	4.5mm
$\sigma_{Heading}$ (95%) = 2 × $\sigma_{Heading}$ (68%)	0.26°

C. Experimental results

The prototype of the innovative system used for the experiments is shown in Fig. 6.

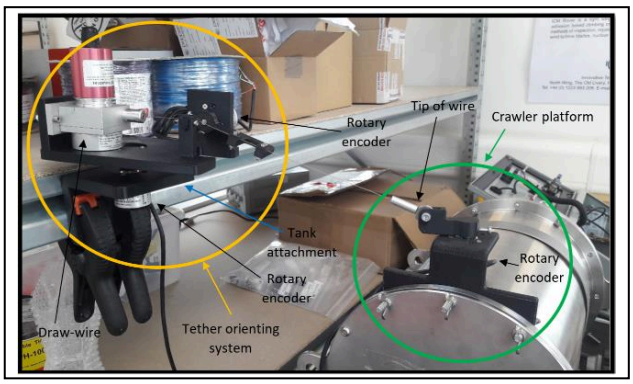

Figure 6. Assembled prototype of the innovative system

The 2D point cloud representing the successive positions of Nautilus is shown in Fig. 7. The point (0 mm, 0 mm) in Fig. 7, denoted by a red asterisk, represents the origin of the localisation system reference frame and is located at the centre of the tank edge bracket.

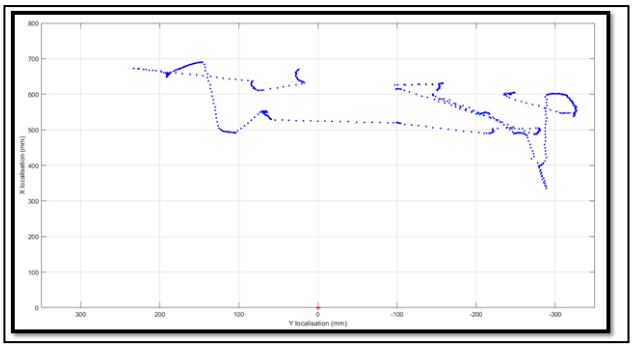

Figure 7. Experimental free space exploration map

From the data collected by the various system sensors after outlier removal, standard deviations of the position and orientation errors, in all directions (X, Y and Z), are calculated and gathered in Table II. The mean calculated for each error (difference between the estimations from the innovative system and from OptiTrack) is near 0, but a slight bias persists: X_{bias} = 36mm, Y_{bias} = 48mm, Z_{bias} = 31mm). This means that there is a slight offset between the system reference frame and OptiTrack reference frame.

TABLE II. COMPARISON OF SYSTEM UNCERTAINTY

Standard deviation (68%)	*Localisation system (experimental)*	*Localisation system (simulation – 1m range)*
σ_X	19mm	1.9mm
σ_Y	23mm	1.9mm
σ_Z	4.7mm	1.4mm
$\sigma_{Heading}$	2.4°	0.13°

The standard deviation σ_Z presented in Table II is calculated for information and used to derive a positional accuracy which can be compared with literature. Since the

experiment has been run for a constant height, the position error only corresponds to a specific height.

According to Table II, there is a clear difference between the experimental results and the simulation results. The higher standard deviation for the prototype can be caused by inaccuracies in OptiTrack marker positioning, a misalignment during the incremental encoder calibration or fluctuating mechanical constraints on 3D printed material, resulting in part bending.

D. Comparison with literature

1) Experimental results

To assess the degree of accuracy achieved by the experimental localisation system, position and orientation uncertainties have been calculated to compare with results found in literature. The positional accuracy and orientation accuracy have been calculated for the experimental localisation system and are compared with state-of-the-art localisation technologies in Table III.

TABLE III. COMPARISON OF SYSTEM ACCURACY

System	***Range***	***Position accuracy (90% uncertainty)***	***Orientation accuracy (95% uncertainty)***
Localisation system(Exp)	1m	39mm	4.8°
Simulation	1m	4.5mm	0.26°
Simulation	5m	18mm	0.26°
Smart Tether	40m	1.5m	0.5°
LBL	100m	0.2m	0.1°

According to Table III, the positional accuracy obtained for the localisation system is better than the one obtained for the KCF Smart Tether or the LBL. However, the orientation accuracy is 10 to 50 times higher. This highlights the fact that there is a significant factor perturbing the localisation system, or that the localisation system technology is not suited for orientation estimations. This issue seems to originate from the prototype, as the MATLAB simulation can provide an orientation accuracy better than the Smart Tether.

When, as a second step, the measurement range is taken into account, it is more convenient to compare the ratio accuracy over range. The comparison between ratios of accuracy over range is displayed in Fig. 8.

According to Fig. 8, the prototype provides a positional accuracy which can compete with the accuracy of the Smart Tether. However, it is outperformed by the LBL which displays an even better ratio than the simulated localisation system. The latter comparison proves that with the current components and their characteristics, it is impossible, even ideally, to beat the LBL results. The performance of the localisation system can be enhanced, but at a higher cost.

Concerning the orientation accuracy ratio comparison displayed in Fig. 8, the prototype is far behind the other systems. Even the simulation designed for the project (5m range) cannot achieve a better orientation accuracy/range ratio than the Smart Tether. The unsatisfactory orientation accuracy confirms that the localisation system is intrinsically not optimised for accurate orientation estimations.

2) Enhanced model

At this stage, the comparison between the experimental results and the literature is not fully relevant, as the localisation system can only be used in the aerial environment and not underwater. Switching one Wisamic encoder with an IP68-compliant encoder might enhance the accuracy but will also influence the cost. The performance comparison is presented in Fig. 8.

Different enhancements have been suggested for the 5m measurement range:

- Underwater model: the rotary encoder on the crawler platform is IP68-compliant.
- Robust model: Sheet metal is used for the mechanical architecture.
- Draw-wire+ model: more performant draw-wire.
- Encoder+ model: more performant rotary encoder.
- Underwater, robust model+: all of the above.

According to Fig. 8, the robust submersible model for 5m measurement range performs better than the LBL and is 300 times less expensive. The simulation results confirm that the developed tether technology is viable for accurate position estimations. This model also outperforms the Smart Tether and is 5 times less expensive. However, the tether technology relying on

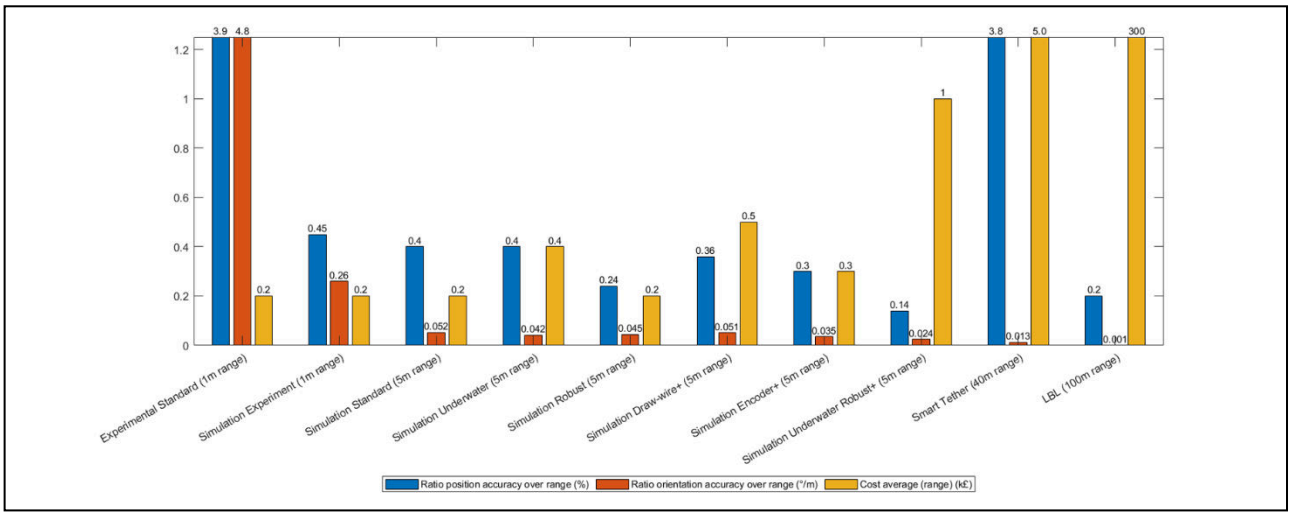

Figure 8. Ratio accuracy over range system comparison

rotary encoders is outperformed by the performance of the compass, according to the orientation ratio results.

An improved mechanical architecture will significantly increase the positional accuracy without major increase in cost, but it will have limited impact on the orientation accuracy. A better draw-wire will increase cost without significantly enhancing the positional accuracy or the orientation accuracy. Better encoders will have a positive influence on the positional accuracy, but most importantly, will lead to an orientation accuracy gain, while having a moderate impact on the cost.

IV. Conclusion

An accurate tether-based localisation system relying on tether technology has been proposed and implemented in this work to serve as a reference tool for other localisation technologies, such as dead reckoning or sonar-based technologies. A prototype has been produced and its positional accuracy and orientation accuracy have been assessed by an extremely accurate and vision-based motion capture system called OptiTrack.

The prototype has been able to determine in real-time (3Hz updates) the position of the centre of mass of Nautilus (robotic crawler), with an uncertainty of ± 39mm over a 1m measurement range (90% confidence interval). It has also been able to determine the heading orientation of Nautilus with an uncertainty of ± 4.8° (95% confidence interval). The prototype has been identified as competitive against other tether-based state-of-the-art solutions such as the Smart Tether by KCF in terms of positional accuracy and cost.

Increasing the rigidity of the mechanical device combined with high performance rotary encoders and draw-wire position sensor, the positional accuracy of the new system could outperform the results from the LBL, while remaining affordable for industrial companies. However, it has been underlined that this enhanced system complying with the research objectives could not outclass the compass, used jointly with tether-based and sonar-based technologies, in terms of orientation accuracy. Nevertheless, the enhanced system has been validated to serve as a reference tool for other positioning technologies, as it performs identically or better than the current best solutions on the market and is cost-competitive.

Another method to increase the accuracy would be to implement supervised learning and involve training an AI model using the real orientation and position data from OptiTrack sensors and correlate it with the data coming out of the innovative system sensors.

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