Tracking and remote monitoring of an autonomous underwater vehicle using an unmanned surface vehicle in the Trondheim fjord

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***Abstract*—This paper presents a demonstration conducted in the Trondheim fjord, where an unmanned surface vehicle (USV) developed and operated by Maritime Robotics AS was used to relay acoustic information sent by a REMUS 100 autonomous underwater vehicle (AUV), to an onshore operation center. The AUVs mission was to conduct a survey of a Short Sunderland type aircraft, which was sunk just outside Munkholmen in 1945. The progress of the AUV and the USV were available in real-time throughout the demonstration, and was presented in Maritime Robotics' in-house Vehicle Control Station (VCS) software. The acoustic telemetry data was also relayed to the REMUS Vehicle Interface Program (VIP), used for monitoring the health of the AUV. Furthermore, the USV used the telemetry messages sent by the AUV, containing e.g. position and heading, to autonomously track the AUV during the survey. Throughout the mission, only 63% of the modem messages was received by the USV, and the longest time between telemetry updates was 6 minutes, but the USVs ability to track the AUV and relay data was successfully demonstrated.**

I. Introduction

Establishing a continuous communication link with an Autonomous underwater vehicle (AUV) while the AUV is conducting its mission is a challenging task. A continuous communication link with an AUV is motivated by fault detection, mission plan updates, and real-time presentation of data. Underwater communication through acoustics are widely used for AUVs, but are limited by range and bandwidth, where the bandwidth decreases as the range increases. To extend the range and to achieve a better acoustic link with the AUV, an unmanned surface vehicle (USV) can be used to relay data, either through satellite or through another form of wireless communication.

An example of an USV used to relay data is presented by McGillivary et al. [1]. In the experiments detailed in this paper, a Delay/Disruption Tolerant Networking (DTN) protocol was used to relay data between an AUV and an USV. The AUV relayed CTD data, as well as sidescan sonar imagery, to a remote operator. Based on the received data, the operator could redirect the AUV as desired, with commands being relayed through the USV to the AUV.

In addition to act as data relay, USVs can be used to extend the range of AUVs in other ways. Ferreira et al. discussed the development of the swordfish USV, which was developed as a survey vehicle, in addition to operating as a mobile air-to-underwater gateway [2]. Another feature of the swordfish USV was the possibility to add a docking station for the Isurus AUV. In the future, USVs with docking stations could dramatically increase the range of AUVs, in addition to reducing the operational cost and complexity of an AUV operation by removing the dependence on ships.

The time an AUV may spend continuously underwater is often restricted by navigation accuracy. If no acoustic transponders are deployed in the operational area, the AUVs navigation system will suffer from position accuracy degradation as time passes. Bahr et al. discussed an algorithm for cooperative navigation for AUVs, using a large set of range measurements between a fleet of AUVs [3]. In the experiments presented by Bahr et al., USVs are used as substitutes for all, or some of, the AUVs to be able to use GPS for evaluating the results. The algorithms performance depends on the navigation error of the navigation aid-vehicles, and Bahr et al. states that the navigation error of the algorithm is bounded only if the navigation error of the navigation aid-vehicles is bounded. Thus, by using USVs, this algorithm can be used to obtain a bounded navigation error for AUVs, without the need for deployment of acoustic transponders.

Previous work related to AUV tracking with an USV is presented by Melo and Matos [4] and by Daxiong et al. [5]. Melo and Matos presented an experiment where the range between the AUV and two acoustic beacons were used by the USV to estimate the position of the AUV, and a PI controller was used to track the USV [4]. Daxiong et al. discussed an experiment where the USV tracks an AUV based on acoustic modem telemetry containing navigation information from the AUV.

Operating multiple unmanned vehicles can be a operationally complex task. The Underwater Systems and Technology Lab (LSTS) at the University of Porto has developed a modular software toolchain for networked vehicle systems [6], divided into three major components, namely DUNE, IMC, and Neptus. The LSTS toolchain has been successfully demonstrated on AUVs, USVs, unmanned aerial vehicles (UAVs), and remotely operated vehicles (ROVs), and cooperative control between AUV and USV have been performed [6]. The toolchain also includes an autonomy plugin, T-REX, easing

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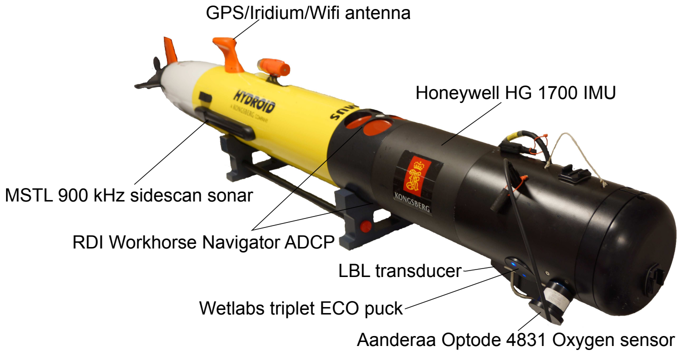

Fig. 1. The REMUS 100 AUV.

Fig. 2. The USV Telemetron.

the programming of new objectives and increasing mission execution safety. T-REX has been tested on AUVs and USVs [7], and on UAVs [8].

Having a common command and control software may reduce the complexity of mixed unmanned vehicle operation. Faria et al. presented an experiment where UAVs and AUVs where coordinated for oceanographic surveys and both vehicle systems where controlled through Neptus [8].

II. Implementation

The demonstration presented in this work involves an USV autonomously tracking an AUV, to extend and improve the acoustic link used for monitoring the AUV. In addition to the two vehicles, four long-baseline (LBL) acoustic transponders was deployed in the survey area, to provide the AUV with a position reference throughout the mission, and a control station was setup at the Marine Technology Centre in Trondheim, providing a real-time overview of the progress of the USV and the AUV. During the experiment, the AUV operator was onshore, monitoring the AUV with the data relayed by the USV. Similarly, the USV was monitored and operated through the online interface. As a safety measure, one operator was idle onboard the USV through the duration of the experiment.

A. Vehicles

1) REMUS 100: The AUV used in the experiment was a REMUS 100 AUV, see Figure 1. The vehicle is 160 cm long, have a diameter of 19 cm and weighs 31 kg. The maximum speed of the vehicle is about 5 knots, and the rated endurance is 10 hours at a speed of 4 knots. The navigation suite consist of a Honeywell HG 1700 IMU, a RDI workhorse Navigator ADCP, a LBL transducer, as well as a GPS antenna for use at the surface. The vehicle can communicate via Iridium and Wifi when at the surface, and relies on a WHOI micromodem for acoustic communication. The survey sensors consist of a MSTL 900 kHz sidescan sonar, a Wetlabs triplet ECO puck, an Aanderaa Optode 4831 Oxygen sensor, and a Neil Brown CTD sensor. The vehicle is monitored and operated using the Vehicle Interface Program (VIP) software developed by Hydroid.

2) Telemetron USV: The Telemetron USV is developed and operated by Maritime Robotics AS, and is a customized PolarCirkel 845 Sport, which is 8.45 m long, 2.5 m wide, and weighs 2400 kg, see Figure 2. The USV has a top-speed of about 37 knots, and uses GPS as navigation aid. For redundancy, several GPS units are installed. For communication, the USV relies on an ICE-modem (using CDMA2000), a VHF-modem, as well as an automatic identification system (AIS) transceiver. The payload sensors consist of a Norbit WBMS multibeam sonar (mounted in the moonpool), an Electro-Optical camera, and radar. The USV Telemetron is monitored and operated through the Vehicle Control Station (VCS) software developed by Maritime Robotics AS.

B. Communication setup

To be able to communicate with the AUV, a WHOI micromodem was mounted in the moonpool of the USV and interfaced with the onboard control computer. Using the ICE-modem, the USV relayed all acoustic modem messages from the AUV to both the VCS and VIP. A state message was sent from the AUV every minute, containing timestamp, position, speed, heading, depth, and destination waypoint [9]. The modem messages was displayed in VIP and used to monitor the status and health of the AUV, while the data was decoded and used to estimate the position of the AUV by the VCS software.

C. Tracking algorithm

Based on the information received in the acoustic modem telemetry, the USV predicted the current position of the AUV. To do this, the speed and bearing of the AUV was considered to be constant between modem messages, and the depth of the AUV was disregarded. Due to potential long periods without modem messages being received, the mission plan of the AUV was used as a backup in the estimator. If the AUV arrived at a waypoint, the estimator would switch to the next waypoint automatically without having to wait for the next modem message with a new target position. When a new modem message was received, the position of the AUV was updated. The USV estimator assumed that the AUV had perfect knowledge of its position, and the AUV position in the estimator was set to the received position (adjusted for time-delay). A snapshot of the VCS showing the position of the USV and the estimated AUV position is presented in Figure 3.

The USV used the constant bearing (CB) guidance scheme for tracking the estimated AUV position. This means that the USV will align the relative interceptor-target velocity vector along the line-of-sight vector between the interceptor and the

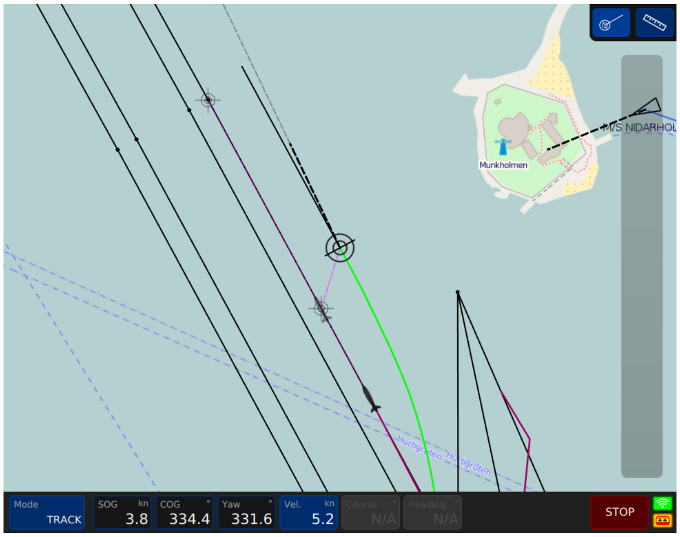

Fig. 3. Snapshot of the Vehicle Control Station software showing the position of the USV, the last known position of the AUV (black), and the estimated position of the AUV (gray).

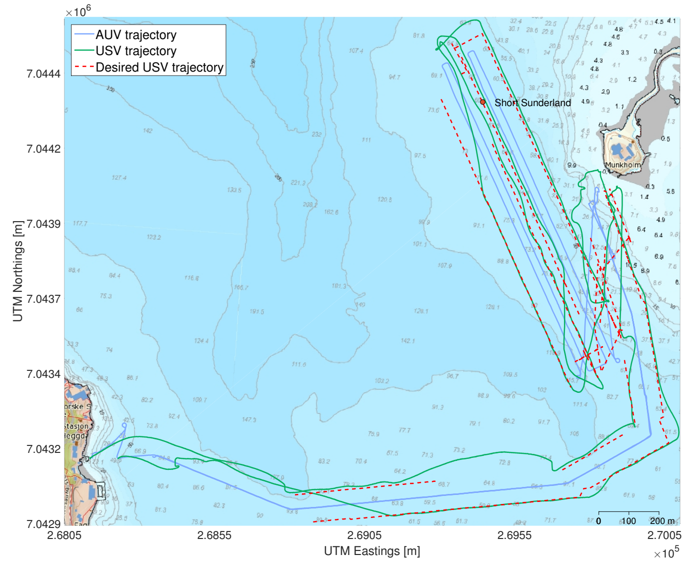

Fig. 4. Trajectory of the AUV and the USV during the experiment.

target [10]. Let $p(t) \in \mathbb{R}^2$ and $v(t) \in \mathbb{R}^2$ be the position and velocity of the USV, respectively. The CB guidance scheme is implemented through the direct velocity assignment

$$v(t) = v_t(t) + v_a(t), \tag{1}$$

where $v_t(t) \in \mathbb{R}^2$ is the target velocity vector and $v_a(t) \in \mathbb{R}^2$ is the velocity along the line-of-sight vector [10]. Denoting the interceptor-target line-of-sight vector $\bar{p}(t) = p_t(t) - p(t)$, the approach velocity can be chosen as

$$v_a(t) = \kappa(t)\frac{\bar{p}(t)}{|\bar{p}(t)|}, \tag{2}$$

where $\kappa(t)$ can be chosen as

$$\kappa(t) = U_{a,max}(t)\frac{|\bar{p}(t)|}{\sqrt{\bar{p}(t)^\top \bar{p}(t) + \Delta^2}}, \tag{3}$$

where $U_{a,max}$ is the maximum approach velocity along the line-of-sight vector, and Δ is a tuning parameter that controls the transition between pursuit and rendezvous with the target. This gives the velocity assignment control law

$$v(t) = v_t(t) + U_{a,max}(t)\frac{\bar{p}(t)}{\sqrt{\bar{p}(t)^\top \bar{p}(t) + \Delta^2}}. \tag{4}$$

The CB guidance scheme is particularly useful for under-actuated vehicles, like the Telemetron USV, since an overshoot would only decrease the velocity of the interceptor to slower than the target, rather than changing the heading [10].

III. Results

The experiment was conducted on the 7$^{\text{th}}$ of May in the Trondheim fjord, as a demonstration in conjunction with the NTNU Ocean week. The objective was to monitor the progress of the AUV with a USV, and to perform all communication with the AUV using the USV as a relay. The AUVs mission was to conduct a survey of a Short Sunderland type aircraft, sunk just outside Munkholmen in 1945. The demonstration showed the USVs ability to track the REMUS AUV, even with a relatively poor acoustic link. Throughout the mission, only 63% of the modem messages was received by the USV, and the longest time between telemetry updates was 6 minutes. The reason for the high loss of acoustic modem messages over the short range has not been thoroughly investigated, but it may stem from a suboptimal mounting of the acoustic modem head on the USV. The modem was mounted in the moonpool of the USV, next to the MBE head, and relatively close to the underside of the boat. Both these elements may have caused some acoustic reflections, causing a poor acoustic link. The setup also caused some vibrations during transit that may have affected the performance of the acoustic modem.

During the demonstration, sidescan images was captured of the Short Sunderland aircraft by the AUV, and the USV captured multibeam echosounder (MBE) data of the whole survey area. A sidescan image of the Short Sunderland type aircraft can be seen in Figure 5.

A. Tracking algorithm performance

An overview of the conducted field experiment is shown in Figure 4. The figure shows the trajectory of the AUV and the USV, as well as the desired trajectory of the USV. From Figure 3 it can be seen that the USV was commanded to stay a distance of 75 m to the starboard of the AUV, at an angle of 45 degrees. This was believed to give a good acoustic link, since the acoustic modem was mounted on the port side of the USV. The desired USV trajectory calculated by the USV is also shown in Figure 4, and it can be seen that some

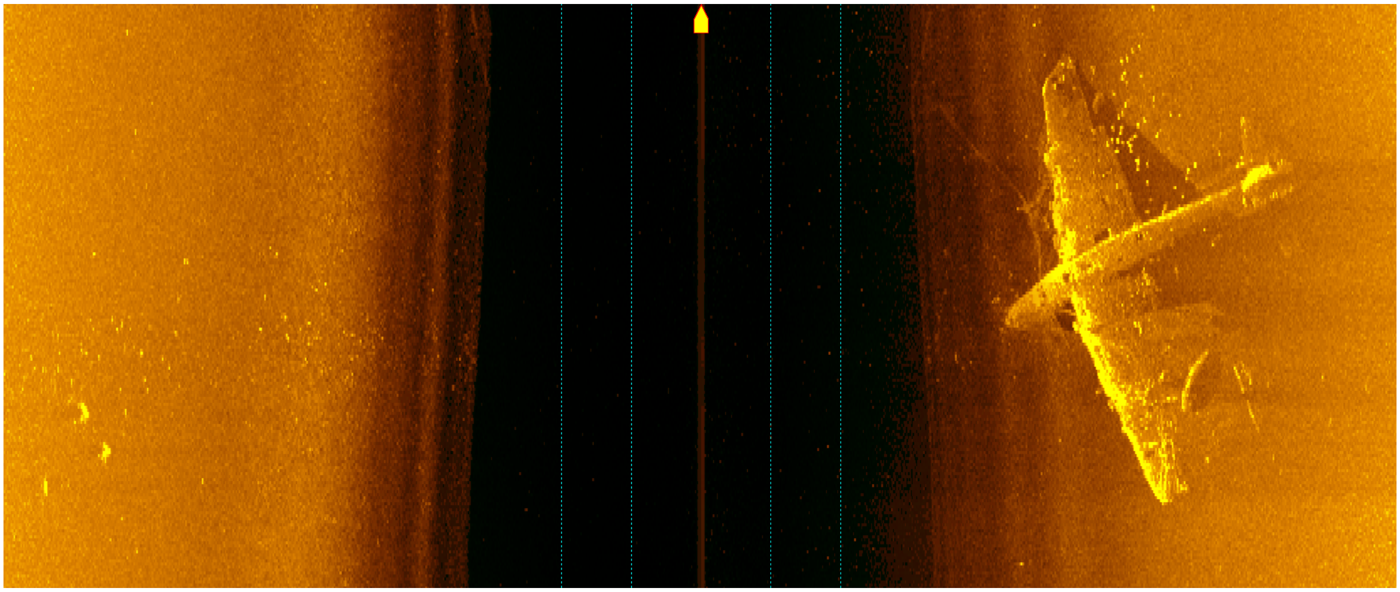

Fig. 5. Sidescan data of the Short Sunderland type aircraft captured by the AUV.

segments lack the desired USV trajectory. These segments indicate areas where the USV tracking mode was turned off. In these segments the USV was remotely controlled through the internet link.

Figure 6 illustrates the performance of the estimated AUV position. The figure shows the absolute error between the estimated northings and eastings position of the AUV and the actual AUV position (as reported by the AUV throughout the mission), and it can be seen that the estimated position follows the real position fairly well. The two first spikes seen in Figure 6 are due to a large position correction performed by the AUV during the first surface and GPS fix objective. The third large spike and the smaller spikes followed by a period of disabled tracking mode (empty segments in the figures) on the USV was due to an error in the implementation of the tracking algorithm. There seem to be a steady state error of approximately 10 meters throughout the whole survey, which can be explained by the resolution of the transmitted AUV timestamp, which has a resolution of 4 seconds.

The performance of the tracking algorithm is presented in Figure 7, showing the absolute error between the estimated USV target (adjusted by the offset lever arm) and the actual USV position. The corrected USV target position can be found from

$$p_{target,\,corrected} = p_{target} - R(\psi_{leg}) \begin{bmatrix} 75\cos\left(\frac{\pi}{4}\right) \\ 75\sin\left(\frac{\pi}{4}\right) \end{bmatrix}, \qquad (5)$$

where $R(\psi_{leg}) \in SO(2)$ is a rotation matrix and ψ_{leg} is the bearing of the current leg.

As can be seen from Figure 7, the USV follows the desired target adequately. The large spikes in Figure 7 corresponds to the spikes in Figure 6, and are due to poor estimation of the AUV position, due to reasons discussed above. The two first small spikes illustrated in Figure 6 are due to a change in the heading of the target, but the USV quickly converges to the target position after altering the heading (see also Figure 4).

IV. Conclusion and Future Work

This paper has presented an experiment conducted with an USV and an AUV, where the USV attempted to track the AUV autonomously, based on acoustic telemetry transmitted from the AUV. The USV was successful in tracking the AUV during the survey, although the remote operator intervened when the estimate of the AUV position drifted due to a logical error in the prediction algorithm. The AUV operator was able to monitor the health and progress of the AUV at a remote location through the interface provided by the USV, demonstrating the use of USVs for monitoring AUV operations.

The estimation algorithm suffered from a low timestamp resolution, causing a steady state error from the actual AUV position. In addition, the estimation algorithm was dependent on the acoustic modem telemetry. During the experiment, only 63% of the modem messages was successfully captured. Moreover, the AUV operator was not able to send commands to the AUV. This is assumed to stem from a suboptimal placement of the acoustic modem head. Siddiqui et al. discusses the use of underwater acoustic models for evaluating the performance of the acoustic link between LBL transponders and an AUV, and the effect of transponder placement in the water column [11]. By building on the work presented by Siddiqui et al., a possible improvement to the acoustic link could be obtained by optimizing the position of the USV relative to the AUV, as well as the mounting of the acoustic modem head, based on an underwater acoustic model.

During the demonstration, the AUV surfaced twice to counter accumulated position errors, and to avoid collisions between the USV and AUV, a safety zone of 75 meters was established around the AUV surface area. The operating area in Trondheim is a busy harbor, with high activity and ship traffic, and using USVs in conjunction with AUVs could increase the

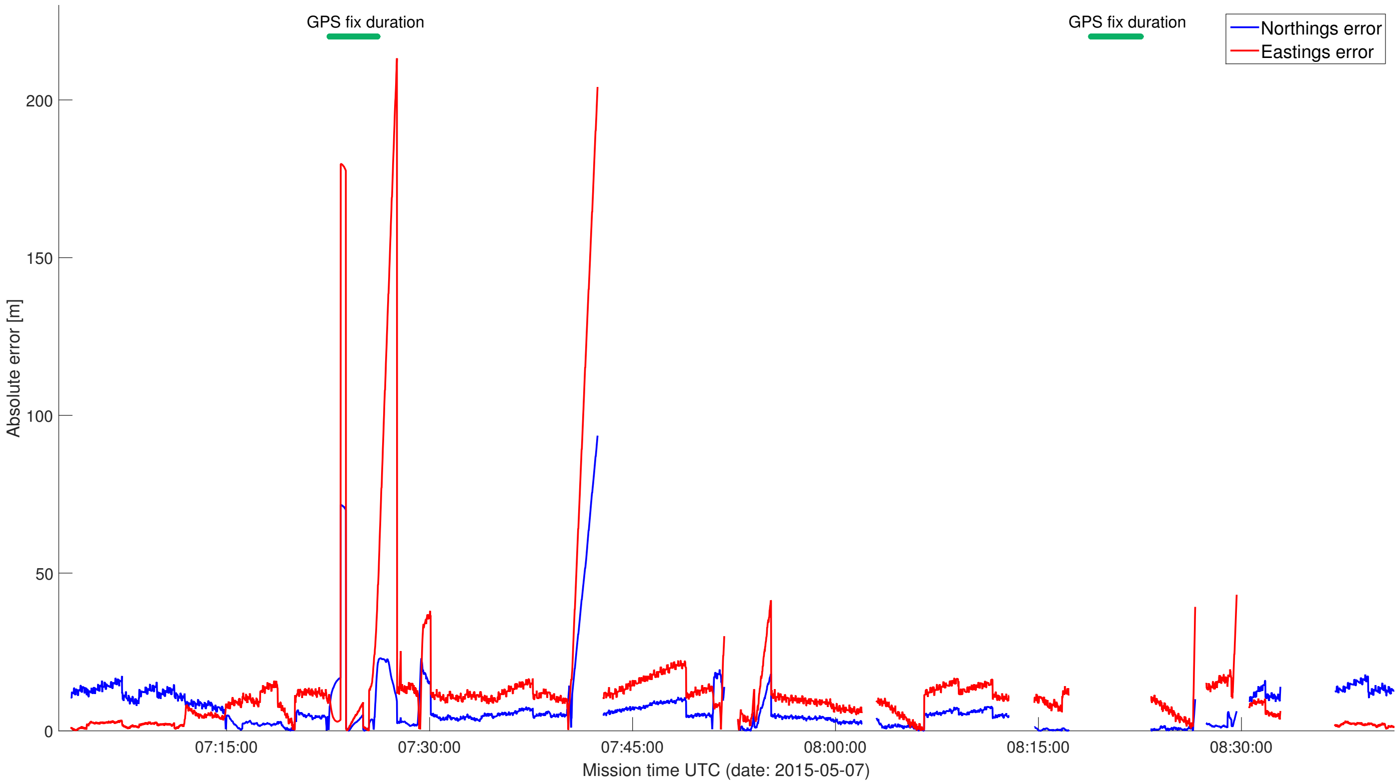

Fig. 6. Plot of the absolute estimation error ($|p_{auv} - p_{target}|$).

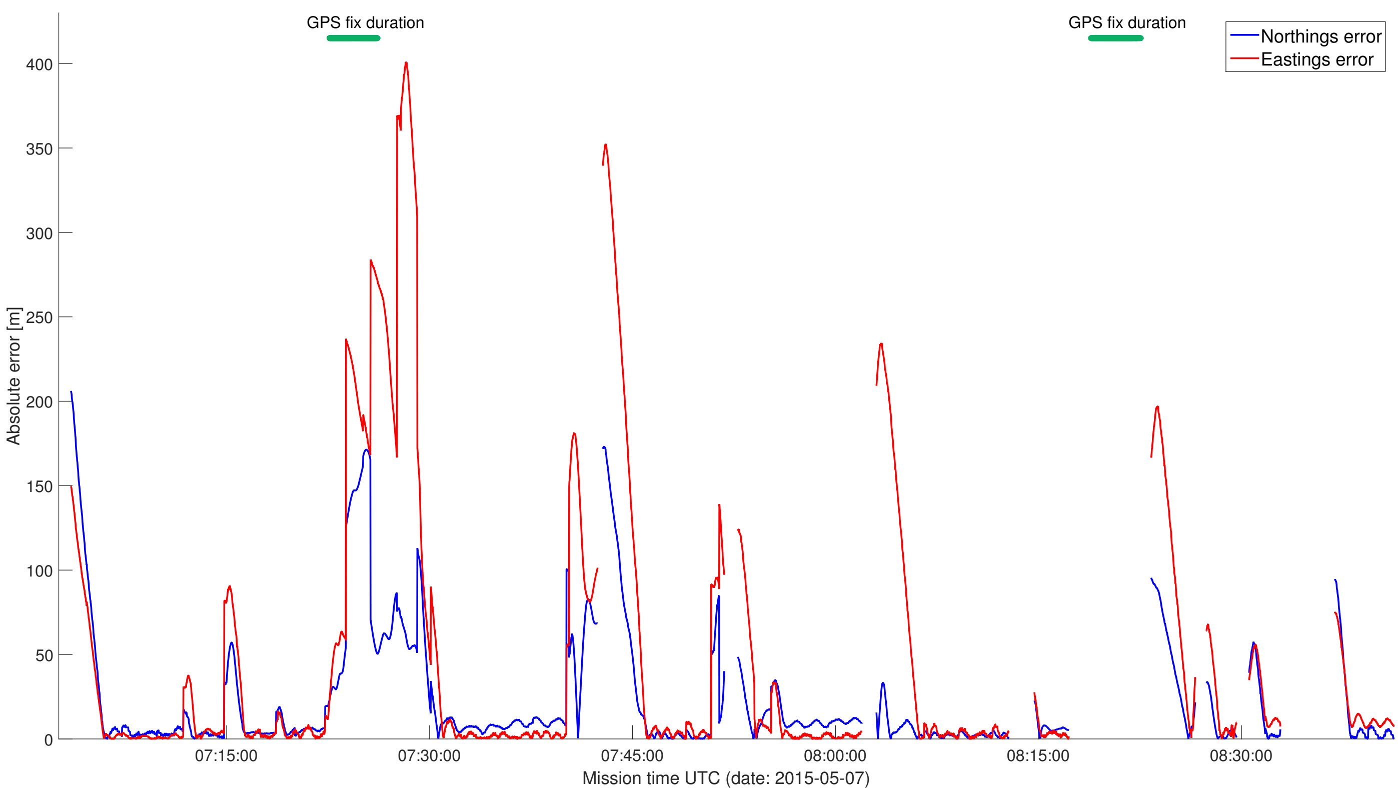

Fig. 7. Plot of the tracking error ($|p_{usv} - p_{target,corrected}|$).

safety of the AUV. Since the USV was equipped with AIS, that exchanges data with nearby vessels, having the USV close to the surface location of the AUV could prevent other vessels from damaging the AUV when at the surface. By patrolling the boundary of the safety zone with the USV throughout the duration of the surface objective, other vehicles using AIS would be aware of activity in this area, increasing the safety of the AUV.

Further work could include a change in the tracking algorithm to rely solely on range measurements between the AUV and the USV, which would decouple the USVs ability to track the AUV from the AUVs ability to estimate its position. This could also be extended to updating the AUVs position based on the USVs estimate. This would extend the time an AUV could safely spend continuously underwater, and lower the operational complexity, by removing the dependency on external positioning transponders.

Additional extensions of the work presented in this paper is a two-way communication link, where payload data from the AUV is relayed in real-time to the USV, and the AUVs mission plan is updated via the acoustic link. Also, to simplify the operational complexity, and to ease inclusion of additional unmanned vehicles (e.g. UAV), the use of open-source software like DUNE and Neptus should be considered. Holsen presents an implementation of DUNE and Neptus for the REMUS 100 vehicle, which could be extended to interface acoustic modem telemetry [12]. The IMC protocol would have to be implemented on the USV, but this way, Neptus could be used for control of all unmanned vehicles participating in the experiment.

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