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UNDERWATER ROBOT SWARMS AND THEIR APPLICATIONS

Özgür YILDIZ [*], Recep Bülent GÖKAL [**], Asım Egemen YILMAZ [***]

Abstract

Research on autonomous vehicles has been a key area of concern especially in the last two-three decades. Underwater vehicles took their share in such studies. In addition to single remotely-controlled and autonomous underwater vehicles, ongoing research deals with construction of coordinated missions to be performed by groups of such vehicles. In this study, which can be considered as a condensed review of the underwater robot swarms, we try to summarize the challenges and practical issues in this area. In addition, we try to illustrate the advantages of a swarm formation with a basic case study.
Keywords: underwater robot swarms, autonomous underwater vehicles, ROVs, AUVs.

1. Introduction

Robots and unmanned vehicles have gained importance in the last decades in order not to risk human life in dangerous operations. Enhancing these unmanned vehicles via autonomy became another attractive research area. Going to more extremes, setting up swarms of heterogeneous autonomous vehicles to help defending high value assets among those has become one of the most interesting and challenging research areas.

In this study, we will try to discuss the challenges of constructing autonomous underwater robot swarms; and give a simple example illustrating the benefits of the swarm by means of our simulator, which is still under development.

Section 1 of this paper can be considered as a review of the autonomous underwater vehicles (AUVs) and swarm intelligence followed by multiple AUV applications; whereas Section 2 summarizes the challenges in the navigation of AUVs; Section 3 is devoted to communication issues. We will try to formulate the AUV swarm construction problem in Section 4, and try to illustrate one of the benefits of the swarm concept in Section 5. Conclusions and discussions will follow in Section 6.

1.1. Autonomous Underwater Vehicles (AUVs)

Several uses of AUVs for oceanographic tasks and military applications have been presented in the literature especially in the last two-three decades. Existing vehicles are showing continuous progress in terms of technology, advanced navigation and control functionalities, longer missions, flexibility and capacity of payload and a very diverse suite of sensors [1-3].

[*] Maleri Technology Inc., Ankara, TURKEY, E-mail: ozgur.yildiz@maleri.com.tr

[**] Maleri Technology Inc., Ankara, TURKEY, E-mail: bulent.gokalp@maleri.com.tr

[***] Ankara University, Faculty of Eng. Dept. of Electronics Eng., Ankara, TURKEY, E-mail: aeyilmaz@eng.ankara.edu.tr

General applications of the AUVs can be listed as oceanographic surveys, bathymetric measurements, underwater maintenance activities (those performed at oil platforms, fiber optic communication lines) and military defense.

A typical military application of AUVs is mine countermeasure (or marine mine-sweeping). Since marine mines are widely used and very dangerous even to the most modern naval forces, tedious and dangerous mine-sweeping activities have become a necessity for many naval operations, and may become increasingly important for domestic security [4]. More advanced military AUV applications are anti-submarine warfare and harbor protection.

Recent advances in the battery technologies and the progress in the fuel cell research studies made autonomous underwater vehicles (AUVs) be used in longer missions possible, which could be performed by manned or tethered vehicles, previously.

1.2. Swarm Intelligence

The term “swarm intelligence”, since its introduction in 1989 in the context of cellular robotic systems [5], has been a major multidisciplinary attraction center for researchers dealing especially with complex design and synthesis problems. Typically, swarm intelligence systems consist of a population with members (i.e. agents) having some characteristic behaviors and interacting locally with each other within their environment. In these systems, the agents individually behave freely to a certain extent and interact with each other. Even though there is no dictating centralized mechanism, these interactions yield a global behavior, which is more organized and directive than that of a stand-alone individual.
Mimicking animal communities, such as those of bees, ants, and fish, has also become the backbone of the approach for defining architectures for cooperation among autonomous robots in several studies (such as [6] and [7]). The basic assumption, observed in several experiments with small robots, verified that from the interaction among multiple autonomous entities “animated” with “social” behaviors, a robust, adaptive, self-organizable structure emerges permitting the achievement of a collective mission rapidly. So far, many examples of robot team tasks have been investigated on a variety of hardware platforms, such as foraging, ant colony behavior, robotic football, map making, area searching, mine sweeping, etc. [8].

Taxonomy for studies related with swarm robotics has been presented in [9]. In [9], the authors suggest major taxonomic units as modeling, behavior design, communication, analytical studies and problems.

1.3. Multiple AUV Applications

Cooperation of multiple AUVs in a single mission can provide enormous advantages in terms of efficiency and efficacy [10]. Cooperation issues in autonomous underwater vehicles [11] constitute a strong research topic.

The potential benefits of multi-vehicle operations are many, and include force-multiplier effects, redundancy avoidance and the utilization of heterogeneous vehicle configurations to reduce risk to expensive assets. Despite these benefits, most of the proposed architectures for such operations in the literature are nothing but simple extensions of single vehicle designs. But ideally, a multi-agent architecture should allow a significant increase in mission efficiency without requiring a proportional increase in communication; which is an important benefit in the underwater environment [12].

Regarding the taxonomy given in [9], we consider that a typical multiple AUV application falls into the following categories:

- Modeling → Sensor-based,
- Behavior Design → Non-adaptive,
- Communication → Interaction via Sensing and Communication

for which the following problems exist:

- Pattern Formation,
- Chain Formation,
- Self-Assembly,
- Coordinated Movement,
- Hole Avoidance,
- Foraging,
- Self-Deployment.

The most common way to coordinate multiple AUVs is what is known as a stoplight system. In these systems, current single-AUV architectures are used to control the vehicles and mission plans are adapted to allow for stoplight points where vehicles can synchronize with each other. The benefit of such systems is that the current single-AUV control architectures can be utilized with a few modifications. However, autonomy is sacrificed because the user has to plan the static sequence of the mission in advance including all synchronization points.

Another approach to multi-AUV cooperation is the modification of existing cooperative robotics approaches for the underwater domain. However, most of these techniques depend on consistent communication, which is a major challenge in underwater [12, 13]. This is mainly due to the fact that the seawater attenuates the majority of the electromagnetic spectrum, causing delays and multi-path effects for the propagating (i.e. acoustic) waves; as will be discussed in the upcoming sections.

2. Navigation of AUVs

Unlike aerial or terrestrial unmanned vehicles, AUVs face a uniquely challenging navigational problem, due to lack of high accuracy satellite-based navigation underwater. Hence, when submerged, they must navigate using several different methods [14].

Three primary methods for the navigation of AUVs exist in the literature [15]:
(1) dead-reckoning and inertial navigation,
(2) acoustic navigation, and
(3) geophysical navigation techniques.

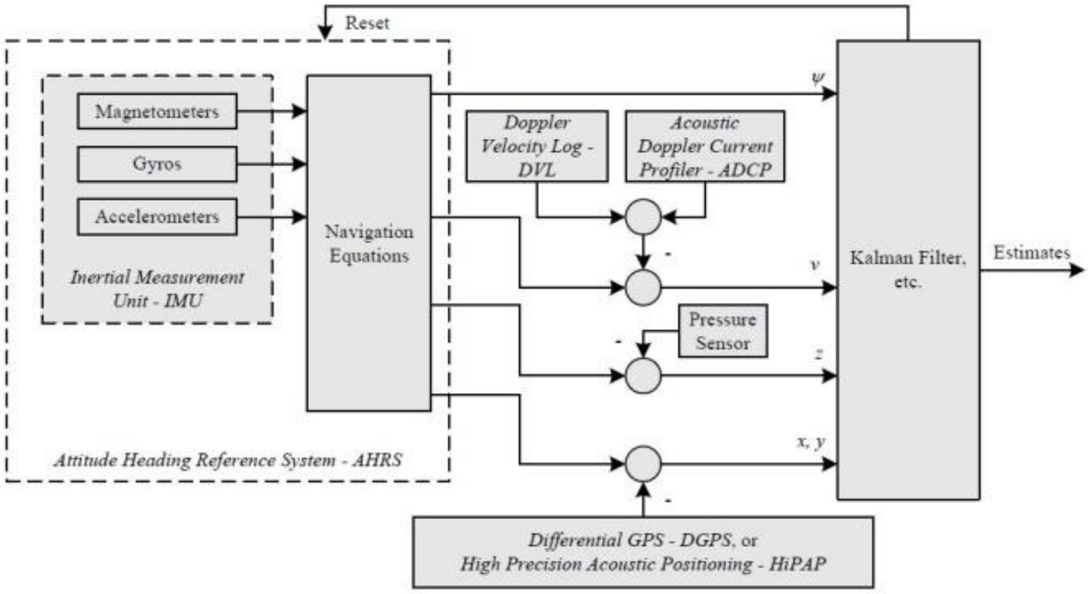

Figure 1. A typical AUV navigation architecture based on inertial navigation systems (based on [16]).

Considering the main application areas of AUVs, navigation accuracy is less critical for oceanographic surveys compared to bathymetric and underwater maintenance activities as well as military applications.

Since the errors in the measurements of inertial navigation equipment (e.g. Inertial Navigation System – INS, Attitude Heading Reference System – AHRS) are monotonically increasing and unbounded, other auxiliary means (e.g. Differential Global Positioning System – DGPS for the position; Doppler Velocity Log – DVL or Correlated Velocity Log – CVL for the velocity; pressure sensors for the depth, etc.) shall be integrated for the navigation aid [16]. In principle, it is recommended to get regular DGPS measurement updates for high accuracy navigation of AUVs [14]. However, this might not be practical especially in under-ice non-military applications, or tactically critical military applications, unfortunately.

Acoustic navigation is based on the usage of acoustic transponder beacons for the AUV to determine its position. The most common methods are the long baseline (LBL), which uses at least two widely separated transponders mounted usually on the sea floor; and the ultrashort baseline (USBL), which uses GPS-calibrated transponders on an accompanying surface vessel. Both methods have a limited range (around 10 km for individual LBL; in deep water, about 4 km, whereas less than 0.5 km in shallow water for USBL networks [14]). Since LBL requires installation of beacons, its applicability is limited to missions performed at fixed-positions (e.g. harbor protection). Moreover, installation and maintenance of the beacons are both difficult and expensive. USBL might not be applicable in some military applications due to tactical restrictions, since it requires an accompanying surface vessel.
Geophysical navigation is based on obtaining an estimate of the position by means of observable physical features (e.g. by existing maps of the area or by construction of such maps during the mission). Even though this technique provides the best accuracy compared to other techniques, it requires expensive payloads with high power consumptions (e.g. optical sensors, cameras) and high computational power. In addition, they are more suitable for missions performed at previously visited areas.

In summary, the AUV navigation sensor set shall be selected according to the mission needs, and appropriate navigation solution architecture shall be defined. A typical AUV navigation architecture is given in Figure 1. As seen in the figure, there is need to combine the measurements of various sensors in order to estimate the position of the AUV together with the errors. The most common method is to utilize the well-known Kalman filter (KF) [17], which is the optimal Bayesian estimator of the state of a system if it is linear, Markovian, and with Gaussian uncertainties. Since the system could not be modeled linearly for the AUVs, extended Kalman filter (EKF) [18] or unscented Kalman filter (UKF) [19] formulation shall be used for the analytical or statistical linearization of the system model, respectively. Particle filter can also be applied for the same purpose [20, 21]. It is also applicable for the cases where uncertainties are non-Gaussian; but it is computationally expensive. Kalman and particle filter formulations are applicable for inertial navigation. For acoustic and geophysical navigation, Simultaneous Localization and Mapping (SLAM) [22] and Concurrent Mapping and Localization (CML) [23] algorithms can be used.

A-priori navigation error analysis is difficult for AUVs, since the navigation error is tightly correlated to the mission profile (e.g. mission speed, mission duration, horizontal and vertical patterns followed, etc.) in addition to the navigation sensor capabilities. Hence, high-fidelity simulations with well-defined scenarios shall be developed and defined respectively for highly accurate navigation error estimations. However, rough error estimates existing in the literature can be used as rule-of-thumb references:

- For short-range missions up to around 10 km, calibrated INS can provide sufficient accuracy for survey missions, regardless of the path taken by the AUV.
- For longer-range missions up to 100 km, the path taken by the AUV has a large effect on the accuracy of the navigation system used. Several geophysical techniques correct incremental inaccuracies in the AUV's position when it returns to a previously visited area. This is necessarily true for any technique that uses a map generated over the course of a mission. If the AUV's path contains many crossover points, then these mapping techniques will perform well.
- Conversely, if the AUV follows a linear path or a single large loop, geophysical techniques provide only a limited improvement from the resulting sequential registration of landmarks and will not significantly aid navigational performance during the mission.
- For missions above 100 km, implementation of an accurate navigation system is more difficult because the best INS will be affected by significant drift over these distances. The deployment of a beacon network over such a large area is not practical and the number of landmarks used by geophysical techniques over such a large area requires more advanced techniques [14].

3. Underwater Communications

Intra-swarm coordination is the key factor for the success of swarm intelligence; hence a well-established communication network is usually desired for such applications. However, as stated before, underwater is a challenging environment for reliable communications with high bandwidth.

An underwater network might consist of AUVs, and other various sensor nodes (either released from surface platforms or moored). Moreover, these surface platforms (if exist) might serve as gateways and provide radio communication links to on-shore stations [13]. Typical acoustic modems that are used to establish underwater links operate at low data rates

and ranges up to a few kilometers. At much shorter ranges of tens to hundreds of meters, communication links with higher performance can be established by using high frequency acoustics. As AUVs move around during a collaborative mission, the inter-node separations may vary from few tens of meters to several kilometers [24].
Since the provided bandwidth is low, message exchange among underwater nodes is limited. Hence, the most common approach for ocean-bottom or ocean-column monitoring is to record data at the nodes instead of exchanging during the mission [13]. Unfortunately, this approach has the following disadvantages [25]:

- No real-time monitoring,
- No on-line system reconfiguration,
- No failure detection,
- Limited storage capacity.

In general, network topology is a crucial factor in determining the energy consumption, the capacity and the reliability of a network. Hence, the network topology should be carefully engineered and post-deployment topology optimization should be performed, when possible [25].

Major challenges in the design of underwater acoustic networks can be listed as follows [25-27]:

- Severely limited available bandwidth;
- Severely impaired underwater channel (especially due to time-varying multi-path and fading);
- High (five orders of magnitude higher than that of radio frequency (RF) terrestrial channels) and extremely variable propagation delay;
- High bit error rates and temporary losses of connectivity (shadow zones) due to the extreme characteristics of the underwater channel;
- Limited battery power, usually incapability of battery recharge due to unavailability of solar energy;
- Failures due to fouling and corrosion.

Regarding the network protocols, the characteristics of the underwater environment shall be considered during the design in order:

- to restore the connectivity quickly when it is lost; and
- to react to unpaired or congested links by taking appropriate action (e.g., dynamical rerouting) in order to meet the given delay bound [25].

In underwater environment, low radio frequencies are less affected by attenuation (compared to high frequency radio frequencies), and offer a suitable alternative for short-range communication with acceptable power consumption and latency; but the limitations on the available bandwidth for data communication still exist [27]. The short range implies that large-scale networks are multi-hop wireless networks. It also implies that the channel can be space-multiplexed between participants sufficiently far apart. In terms of local and global information distribution in swarms, limited range radio links are actually an advantage [27].

Traditionally submarines have relied on acoustic waves for underwater communication. However, acoustic waves in water have large propagation distances, which imply that the links are long range. For instance, at a carrier frequency of 30 kHz, the waves are attenuated by only 0.3 db/m. However, this is not ideal for small submarines in a swarm. Further, multi-path makes the decoding of the transmitted signal difficult even for high received signal to noise ratios. Therefore, if a large distance separates two nodes in a swarm, then the signals transmitted by one will reach the second one but cannot easily be decoded. Hence, two nodes that are not connected with each other might still interfere with each other causing a collision and will therefore disrupt the scheduling algorithm. Moreover, large latencies will cause another problem. Finally, acoustic communication requires large modems, which might be a problem for submarines in a swarm that are designed to carry only small payloads [27].

Long wave radio communication is a possible alternative to acoustic communication. However, if the wavelength is very long, then big antennas will be required, which is again a problem for submarines that carry small payloads. Therefore, a high carrier frequency needs to be used for swarm communication. However, since high frequency radio waves are severely attenuated in the underwater environment, the carrier frequency needs to be carefully chosen [27].

Using electromagnetic waves for underwater communication ensures that links have short range, and long-range interference is minimal. This means that short-range links are better suited for swarm communication [27].

4. Problem Statement

As a matter of fact, the underwater robot swarm constitution problem can be stated as a multi-objective optimization problem for which the following (at least a subset) are tried to be achieved synchronously:

- Minimization of:
  - Cost,
  - Power consumption,
  - Mission completion time,
  - etc.
- Maximization of:
  - Coverage area,
  - Quality of Service (QoS),
  - Navigation accuracy,
  - Situation awareness,
  - Endurance,
  - etc.

In addition, current and potential research topics in such problems include (but not limited to) the following [28-30]:

- Spatial organization necessary for achievement of the relevant mission,
- Forms of cooperation for the given set up subject to given constraints,
- Alternative feedback loops among the swarm members (due to heterogeneity of the swarm members, namely the existence of high and low ability members),
- Implicit and explicit rules of coordination with the objective of maximizing the collective success,
- Types of messages exchanged by the swarm members,
- Forms of redundancies and recovery from adverse circumstances.

5. Case Study

As an example emphasizing the synergistic mechanism of the swarm concept, a scenario comprising an AUV swarm operating in the Marmara Sea is presented. For this case study, the very basic leader-follower scheme is assumed. The storyboard of the scenario can be summarized as follows:

- The leader, which is the highest value asset of the swarm, navigates close to the sea surface. It has the necessary means for measuring the positions and the velocities of the other swarm members, and sending these data periodically to the relevant members.
- The followers, which are low value assets, navigate close to the sea floor in order to accomplish a single task all together in a coordinated manner.

A typical leader-follower formation control approach (e.g., [31, 32]) assumes only one group leader within the team. In this case, only the group leader has the knowledge of group trajectory information, which is either preprogrammed in the group leader or provided by an external source. The formation is then built on the reaction of the other group members to the motion of the group leader.

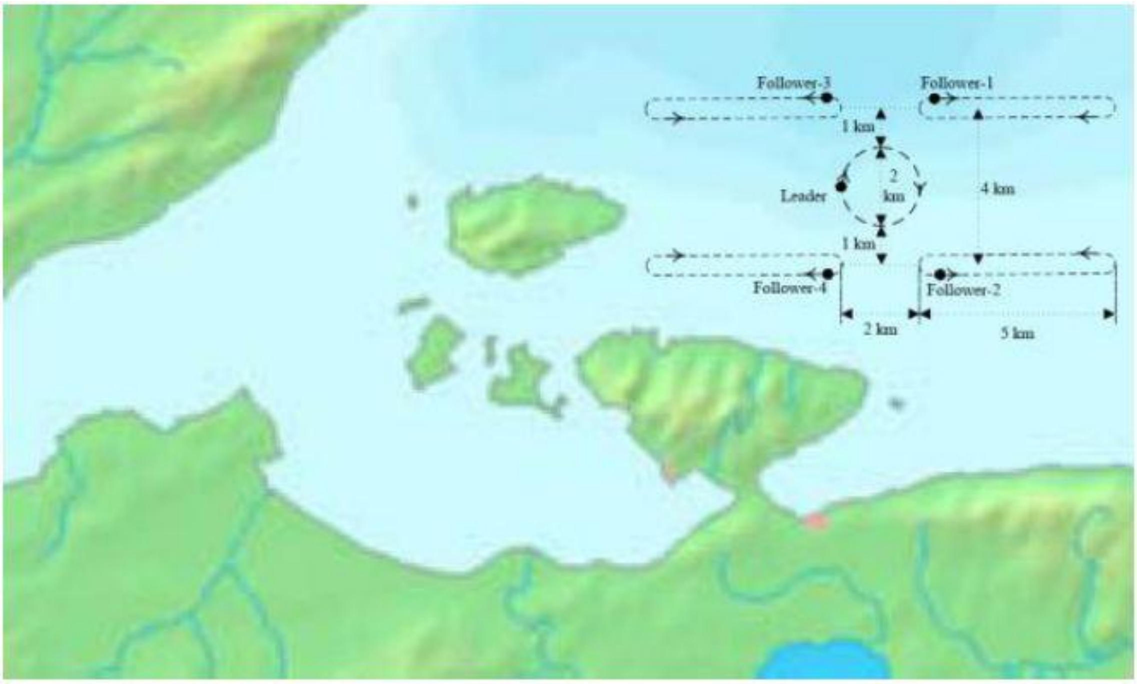

Figure 2. An example leader-follower AUV swarm application (Conceptual top view of the scenario).

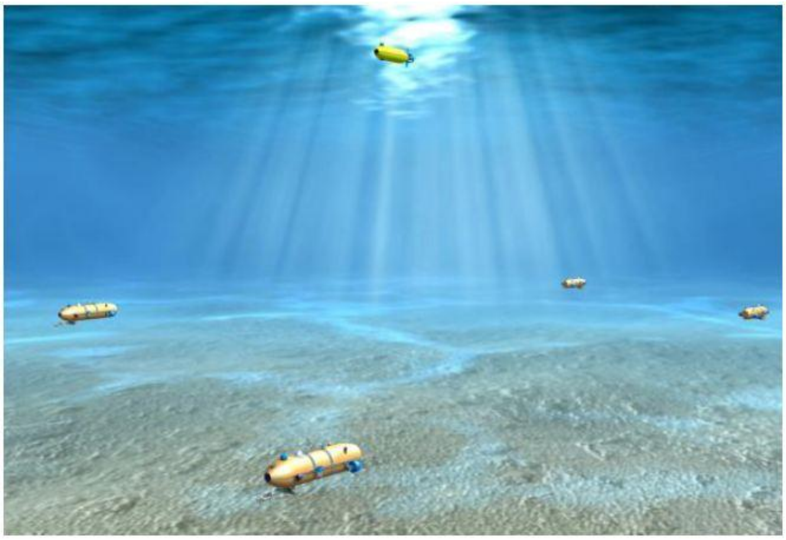

Figure 3. An example leader-follower AUV swarm application (3D view).

The fact that only a single group leader is involved in the team implies that the leader-follower approach is simple to implement and understand, and the usage of communication bandwidth is reduced. This is, however, a single point of massive failure type system because the loss of the group leader causes the entire group to fail. Another issue with the typical leader-follower approach is the lack of inter-vehicle information feedback throughout the group [33]. In order to overcome this type of single point of failure tendency, much research has been focusing on decentralized or distributed cooperative control strategies where vehicle control laws are coupled and each vehicle makes its own decision according to the states of its neighbors (e.g., [34-36]). This allows the group to continue the mission even in the presence of failure of any group member.

The top view of the formation is seen in Figure 2, and the distribution in the third dimension (i.e. depth) is seen Figure 3.

In the scenario, each follower AUV is assumed to be with a constant speed of 3 knots and a constant heading of 45. The scenario duration is 51 minutes, in which the leader AUV supplies the position and velocity update every 10 minutes to the followers.
In order to observe the Kalman filter performance at the noisy measurement environment, the process covariance is assumed to be sufficiently small (i.e. a process covariance matrix with 10-6 diagonal element values, and 0 off-diagonal element values). For the follower AUV, the position measurement error is assumed to be zero-mean Gaussian (with an initial variance of 2 m for each dimension, and monotonically increasing by 0.1% every second). Similarly, the velocity measurement error of the AUV is also assumed to be zero-mean Gaussian (with a constant variance of 0.04 knots). This coincides with the practical situation since AUVs close to the sea floor will suffer from positional drifts of inertial systems, whereas they will be able to obtain robust velocity measurements from the DVL/CVL.

The differences between two operational cases are investigated: (a) the case where the updates from the leader are not processed by the followers, (b) the case where the updates from the leader are processed in order to improve the navigation solution. The results regarding the position estimates, the position errors, and the velocity errors are given in Figures 4, 5 and 6, respectively.

In both cases, the deviation from the planned trajectory for a follower AUV is investigated. As seen in Figure 4, there is significant improvement in the planned vs. actual trajectory conformance.

In Figure 5, it can be seen that the position errors at each dimension are dramatically reduced by means of the updates provided by the leader. On the other hand, as seen in Figure 6, the reduction in velocity error is negligible. This is an expected result, since the velocity measurements of the followers are sufficiently accurate due to their proximity to the sea floor and robust DVL/CVL measurements as stated before.

In Figures 4 to 6, it can be seen that a few smoothers (such as the Rauch-Tung-Striebel (RTS) smoother [37] and the so called “Two-Filter” approach due to smoothing of Kalman and RTS filter outputs [38, 39]) in addition to the Kalman filter are implemented. These filters could not be used inside real-time applications during the mission, since they require forward (i.e. future) measurements and estimations. Hence, they are used in order to get an idea about the upper limits of the accuracy to be achieved, in this study.

At this point, it should be emphasized that even a -position/velocity update of 10-minute is sufficient for the followers to correct their own positions. As a matter of fact, due to low communications bandwidth, more frequent updates might not be possible.

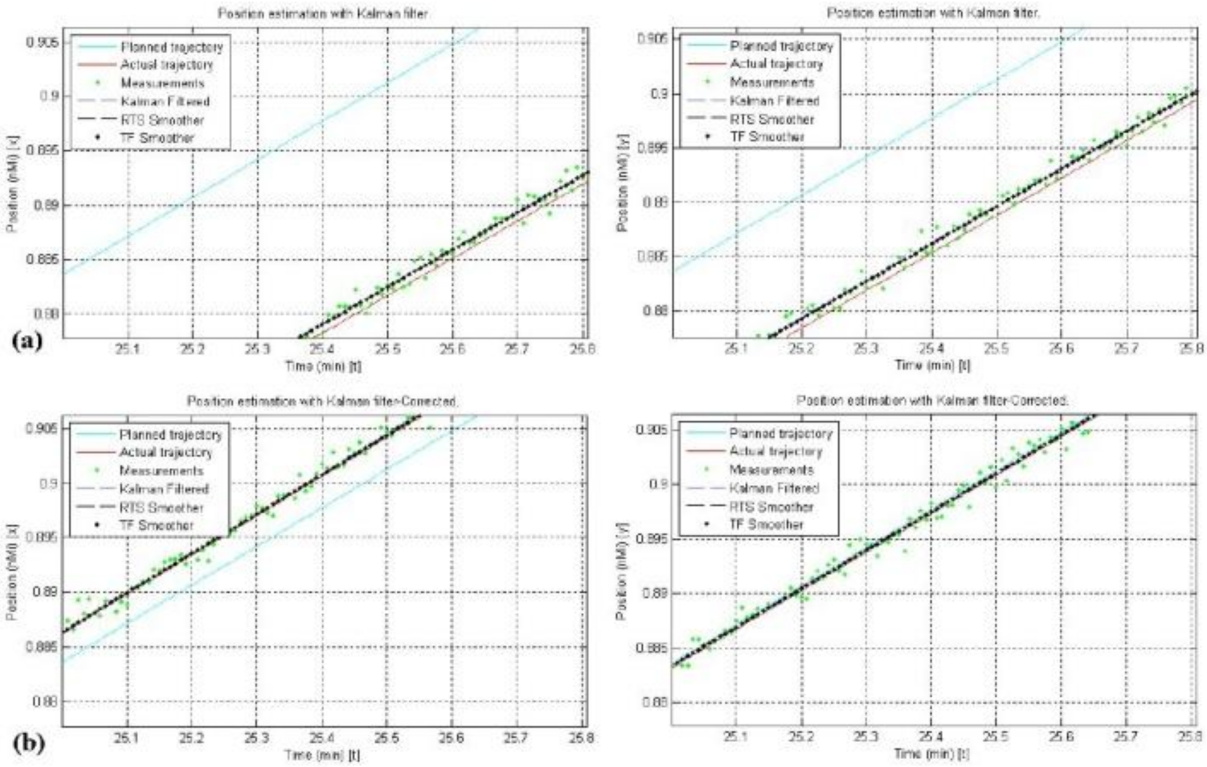

Figure 4. Position estimates (a) No correction by the leader; (b) Correction by the leader.

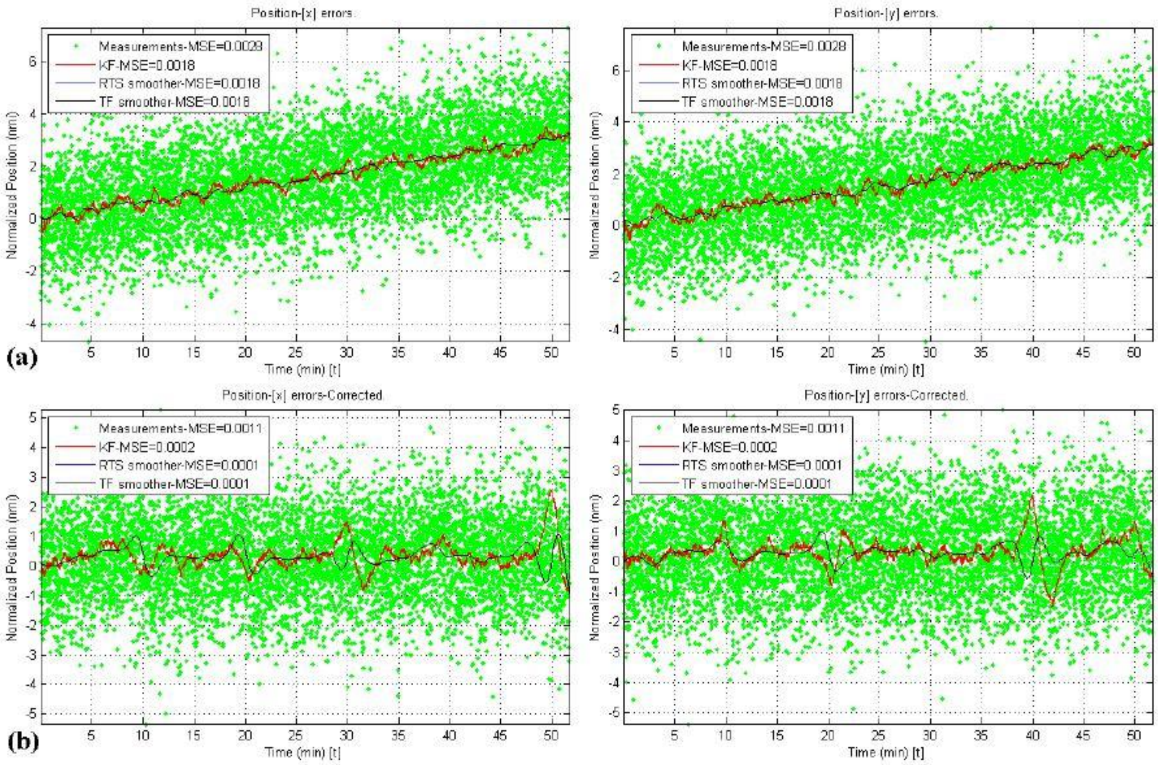

Figure 5. Position errors (a) No correction by the leader; (b) Correction by the leader.

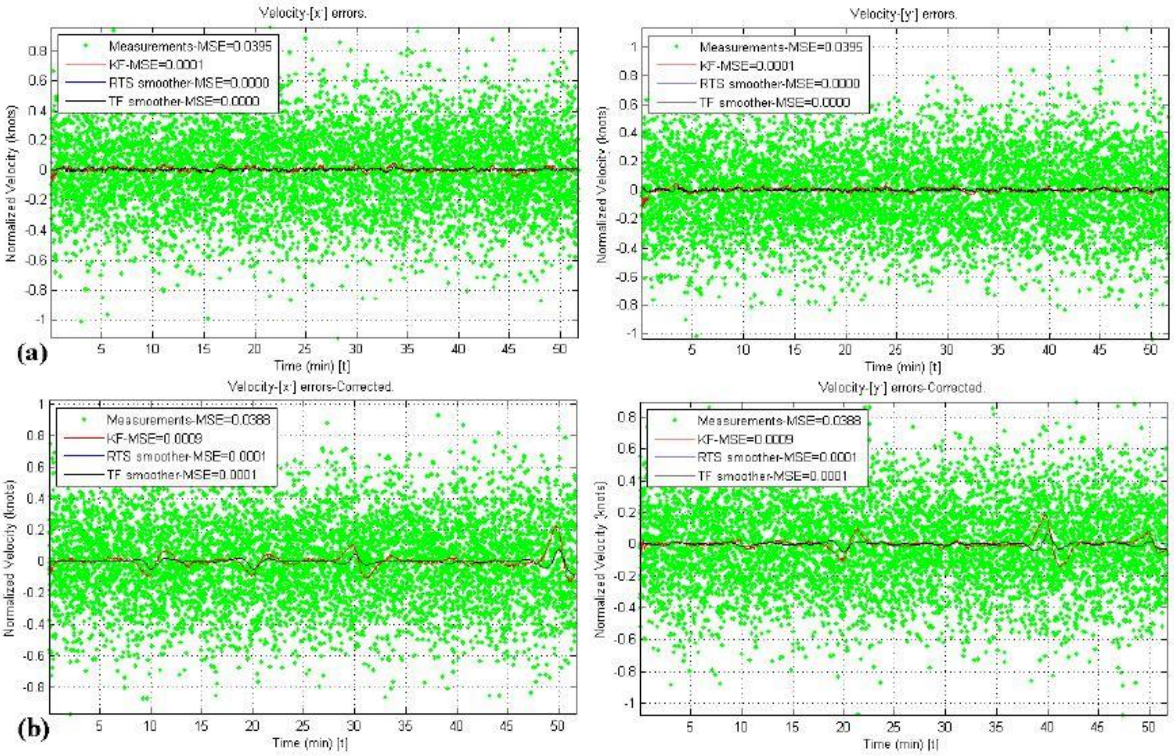

Figure 6. Velocity errors (a) No correction by the leader; (b) Correction by the leader.

6. Conclusion and Future Work

In this study, the applications of AUVs and AUV swarms are discussed together with the practical issues and challenges of navigation and communication.

Even a very basic case study has illustrated the advantages and benefits of the swarm concept about the navigation accuracy. The ongoing studies of our research group about the underwater robot (particularly ROVs and AUVs) swarms can be considered in two directions. The former is the development of the stand-alone unmanned (remotely controlled and autonomous) underwater vehicles, and the latter is the development of an underwater environment simulator, which will serve as a test bed for the navigation and control architecture solutions. The current version of the simulator is a MATLAB software package, which is based on the toolbox presented in [40].

For the time being, other effects of the communication (delays, multi-path, errors, etc.) were not modeled. Ongoing research is dealing with the inclusion and modeling of such effects in order to increase the simulation fidelity. The scenario infrastructure is also being enhanced in order to support more advanced formation schemes in addition to the leader-follower.

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