Cooperative Positioning of Multiple AUVs for Underwater Docking: A Framework

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***Abstract*—Autonomous robots are currently limited by power supply capacity which introduced constraint in term of operation period. Solar system provides possible solution for a workspace exposed to the direct sunlight, but does not work in an underwater environment. Thus, an underwater docking is important for battery recharging for the underwater vehicle especially autonomous underwater vehicle (AUV) after deployment. An accurate docking system requires an accurate positioning system. In this paper, a framework of a sophisticated docking system is proposed for multiple AUVs operation with swarm of autonomous surface vehicles (ASVs) as the position guidance. Swarm concept could increase the operation scalability where a wider workspace could be explored. This proposed system is divided into three major subsystems: underwater localization system, ASVs cooperative system and underwater docking system. It is expected that this system could lead to a reliable, flexible and prolong AUVs operation time for the underwater tasks such as underwater surveying and monitoring. Realizing the idea as a complete system is very challenging tasks but with the proposed system architecture, it is expected that it provides a complete design reference for the future development.**

***Index Terms*-- cooperative navigation, underwater localization, swarms robot, AUV docking, ASV, underwater monitoring.**

I. Introduction

THE development of underwater vehicles have improved method of underwater surveying, monitoring and tasking techniques. However, there are many challenges remain unsolved for technology maturity and operation reliability such as underwater communication, vehicle positioning, data transfer and vehicle power sources. Cooperation of multiple AUVs has recently grabbed the researcher attention because it provides performance improvement in terms of coverage area, data accuracy and task completing capability. In this paper, we will cover three major sections of the aforementioned problems: underwater localization, cooperative AUVs and underwater docking for power recharging. Thus, a review on these three areas of research will be presented in this section to evaluate state of arts and current progress in respective research fields.

Underwater localization or positioning is very important for underwater operation especially after deployment of the underwater vehicles. There are three common principles used for underwater positioning known as ultra-short base line (USBL) or sometimes called super-short base line (SSBL), short base line (SBL) and long base line (LBL) system. In addition, GPS Intelligent Buoy (GIB) is known as the latest method has been used for underwater positioning system. However, these methods of underwater positioning are solely depending on the fixed beacon or limited range of baseline. Thus, it limits the potential of discovering large area of operation and time consumption moving from one area of operation to another. Basically, position estimation is based on time-different-of-arrival (TDOA) or time-of-flight (TOF) estimation of acoustic signals between a transponder and a receiver array placed on the vehicle [1]. The accuracy of time measurement affects the accuracy of position to be estimated. To solve this problem, by taking more reading at an instant a more accurate result can be obtained. Thus, to take more reading at an instant we need more platforms that perform simultaneous reading.

Swarm robotic is a new approach to the coordination of multirobot systems which consist of large number of robots and inspired from social insects or social animals [2]. Examples of swarm robots that have been used for localization applications are swarms of autonomous quadcopter used for object localization [3] and localization using triangulation in the swarms of autonomous rescue robots [4]. In addition, swarm robot also has been used for target's position estimation [5], deployment and localization of the sensor nodes [6], surveillance, target acquisition, and tracking [7] and last but not least for distributed simultaneous localization and mapping (SLAM) [8]. A unique example of the swarm robot implementation for underwater application is acoustic signal tracking for underwater mobile robots [9]. In general, swarm robots for underwater applications are still lack of research attention. From best of our knowledge, most of the related research works has been published used a single ASV to support AUVs navigation [10], [11]. At most, two ASVs have been used where general framework was developed for cooperative navigation in [12]. From the above discussion, we could observe the possibility of using swarm robotic system to replaces single ASV as baseline platform or beacons installation site for the underwater positioning system. S consequence, swarm robots could efficiently track and localize position of multiple AUVs simultaneously during operation.

There are many ideas of AUV cooperative navigation has been published in the literatures. The idea of cooperative positioning using range-only measurements between survey AUV and beacon AUV is one of those ideas [13]. Survey AUV is equipped with sensors required for survey whereas beacon AUV is equipped with high accuracy navigational sensor. By using acoustic communication, beacon AUV helps the survey AUV to improve its positional accuracy by sharing its own location to the survey AUV periodically. Then, the survey AUV will estimate its distance from beacon AUV by measuring the propagation delay of the acoustic signal. By using this information, the survey AUV is able to reduce error of position estimated in the radial direction of the ranging circle centered at beacon AUV. However, the error in the tangential direction remains unchanged. Commonly, the members of a group of AUVs exchange navigation information with one another so as to improve their individual position estimates [14].

In Moving Long Baseline (MLBL) system, two AUVs are used as mobile beacon nodes [15]. They are configured with high accuracy navigation system. These two mobile beacons are positioned on the sides and at the rear of the other AUVs to form the moving baseline array. The mobile beacons will resurface to obtain GPS data periodically. All the vehicles will synchronize to GPS time before submerge. The mobile beacon will give out a pre-scheduled ping followed by its own position. Upon reception of the ping, the other AUVs will be able to calculate their range to the mobile beacon. They will use this range information to correct their prediction of position. An alternative approach which integrates position information of other vehicles to reduce the error and uncertainty of the on-board position estimates of the AUV without going for surfacing. This approach uses the acoustic modem to exchange vehicle localization estimates while simultaneously estimating inter-vehicle range [16].

Multiple AUVs cooperative system has the advantage of allowing AUVs to work together on a common goal without involvement of human action. Every AUV in the system, however, does not have plenty of energy and limited amount of data storage. By using a ship or surface vessel to recover each and every AUV will skyrocket mission costs. Therefore, a mobile or floor-standing station is a better approach to realize a longer AUV mission execution while cutting additional costs needed to send a ship to retrieve the AUVs. As an AUV recharges its battery and transmits or get data through the station, the capability of the AUV to autonomously docks inside the station is of importance consideration.

There are many research had been conducted in developing efficient and reliable docking methods for cruising AUVs, most notably on REMUS100 as described in [17, 18]. As for the station types, although a mobile station is easily manageable [19], a floor-standing station is more scalable [20] and stable from the effect of wave and water current. In contrast to cruising AUV, reports on docking methods for hovering AUV are limited but still available as presented in [21]. In short, a lot of research had been devoted into polishing the docking technique for single AUV, but to date, there is no research has been done on the docking of multiple AUVs. Apart from discerning localization and multiple AUVs cooperative methods, this paper also proposes a novel docking method for multiple hovering AUVs on solving the issue of power limitation.

II. SYSTEM ARCHITECTURE

The overall system of the proposed idea is illustrated in Fig. 1 but not included the docking station. This system consists of three subsystems namely underwater localization system, AUV cooperative navigation system and underwater docking system. The overall process of the system is described in the block diagram as shown in Fig. 2 and flow chart in Fig. 3.

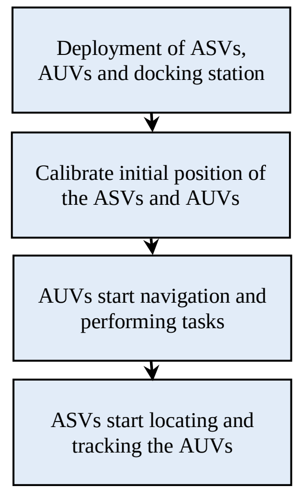


Fig.2. Initialization process

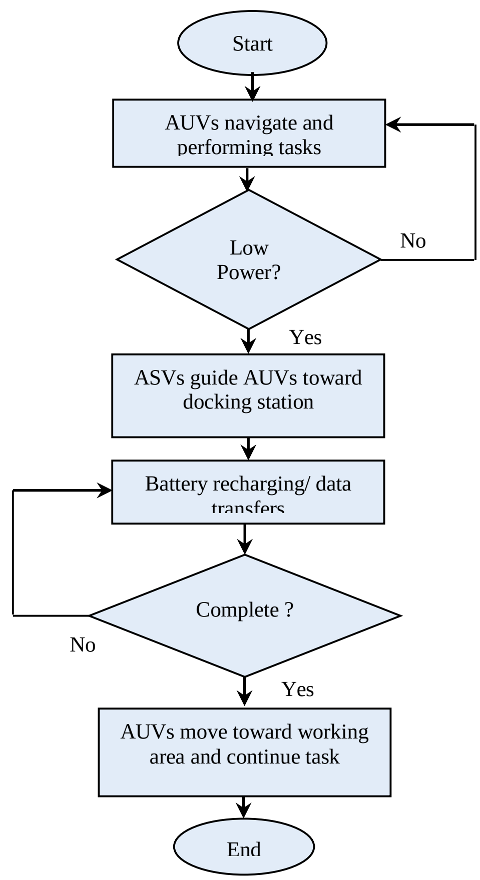


Fig. 3. Docking process

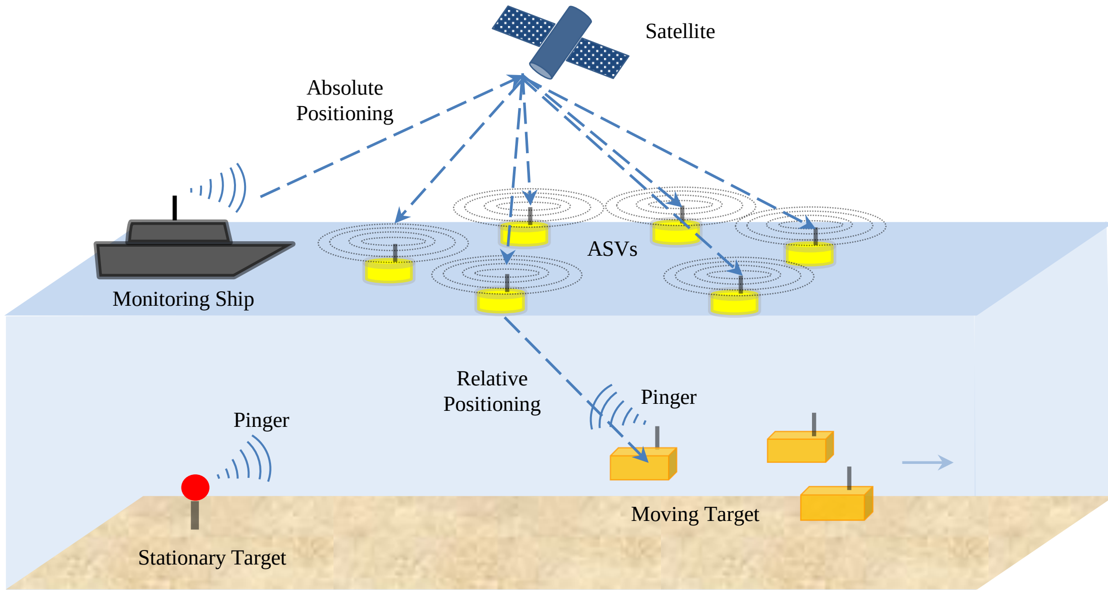


Fig. 1. Proposed method of underwater acoustic postioning

From Fig. 2, the process starts by deploying the ASVs, AUVs and docking station by the deployment ship to area of interest. Once the deployment is done, the initial position of the AUVs and ASVs is calibrated using the attached GPS. The position of the docking station is also recorded. Once the initial position is recorded, the AUVs now can start cooperative navigation and performing their task accordingly. At the same time, ASVs will track the position of the AUVs from the surface and report it to the deployment ship. Since, the position of the AUVs with respect to ASV is relative, some manipulation of the position is necessary to relate the AUV's position to the position of the monitoring ship. The process continue until any of the AUVs encounter low power or need to transfer data to the deployment ship as demonstrated in Fig. 3. Once the AUV send signal of low power to the ASVs, the ASVs will guide the AUVs towards the docking station. After completing power charging or data transfer, ASVs will guide the AUVs back to the working area to continue their task. The detail of each system involves will be explained in the next section of this paper.

Self-localization of an underwater vehicle is particularly challenging due to the absence of GPS signal or features at known positions that could otherwise have been used for position computation. Thus, we have proposed ASVs swarming as a solution for invisibility of the GPS in underwater environment. By using swarm robotic platforms equip with GPS and acoustic devices i.e. acoustic sensor such as hydrophone, underwater absolute positioning is possible to be obtained. Note that ASVs battery is recharge from solar panel and thus eliminates the power issue.

A. AUV Positioning

The proposed concept of underwater localization is illustrated in Fig. 4. Note that the localization only involves a leader of the AUVs to be tracked by the swarm ASVs. The master-follower concept implemented in the cooperative AUVs reduced the complexity of the tracking system. In this case, the positions of the other AUVs are locally measured with respect to the AUV master using acoustic modem installed on each of the AUVs. The detail explanation of this principle will be explained in the next section. Referring to Fig. 4, acoustic signal with specified bandwidth of frequencies is emitted by the AUV (Master). This signal is then detected and measured by the hydrophone array attached to each of the ASVs. Since we would like to obtain x, y and z-coordinates of the master AUV, we need at least four hydrophones in an array to satisfy the geometrical solution of an unknown coordinates. This process is known as multilateration which depends on TDOA values where the principle is illustrated in Fig. 5. The solution of the multilateration process could be obtained in [22] where a closed form of spherical intersection representing TDOA and unknown position is presented.

TDOA of the acoustic signal is recorded by the ASVs internal processor and timer. The value for at least three TDOAs from at least four hydrophones will be recorded. The three values of the TDOA will be used by the processor to perform multilateration of the incoming signals. The position of each of the ASVs is determined by the GPS attached on board. Thus, the accuracy of the position measurement depends on the accuracy of the GPS and accuracy of TDOA estimation used to locate the position for each of the ASV.

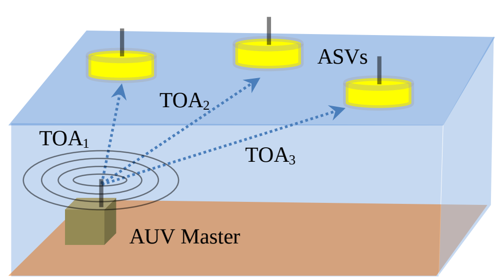


Fig. 4. Illustration of the acoustic signal retrieving

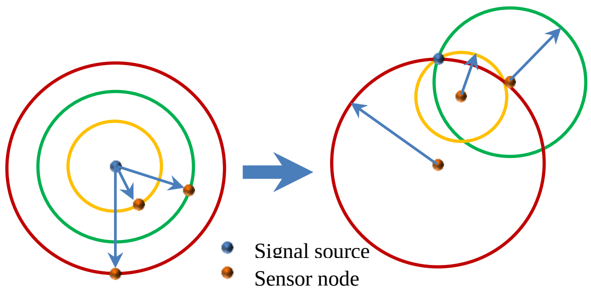


Fig. 5. Illustrations of multilateration concept

There are several method could be employed to estimate TDOA. Cross-correlation (CC) is among the most basic principle to measure time lag between the two incoming signals. However, this method doesn't not guarantee sharp edge to represent maximum time lag i.e. TDOA. To sharpen the CC, a weighting function known as Generalized Cross-Correlation Phase Transform (GCC-PHAT) is introduced [23]. Another method known as Maximum Likeliness (ML) also successfully sharpens the edge but the PHAT is performed better in term peak clarity. The performance comparison of these methods is shown in Fig. 6. In addition, GCC-PHAT is proved to be robust in the reverberated noisy environment and become the most suitable candidate for our purpose [24]. The GCC-PHAT for a noisy signals S_i and S_j is mathematically given by

$$[S_i * S_j][n] = \sum_{k=-\infty}^{+\infty} S_i^*[k] S_j[n+k] \tag{1}$$

and the respective TDOA is given by

$$TDOA_{ij} = argmax([S_i * S_j][n]) / F_s \tag{2}$$

where F_s is the sampling rate.

The overall process of localization is illustrated in Fig. 7. From the multilateration process, the position of the ASV is determined with respect to the earth coordinate (i.e. inertial coordinate frame). The multilateration algorithm is instilled in every ASV so that each of them could perform multilateration based on the set condition. Each of the ASV will share the estimated position among each other wirelessly so that the each ASV knows their correct direction of navigation after comparisons between each other. This data is then used in navigation controller as shown in Fig 8 as reference position. After comparison is made one of the ASVs will decide the correct position of the pinger and will inform other ASVs about the location of the AUV. This approach avoids the position reporting from all ASV at the same time and caused information overlapping and confusion. Finally, all ASVs will move according to the computed coordinate in a specific pattern of formation. This method might take several microseconds before location is confirmed depending on the processing speed and the accuracy of the processor.

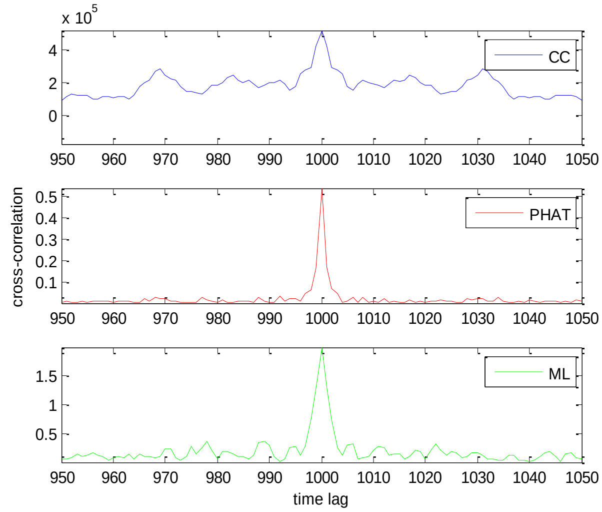


Fig. 6. Comparisons of the TDOA estimation method

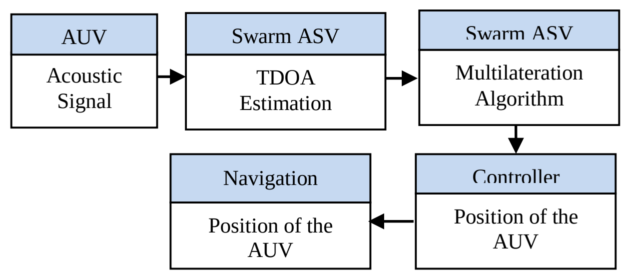


Fig. 7. Overall localization process

B. *AUV Tracking*

Once the position of the AUV is known, the ASVs will move towards the latest updated AUV's location based on the navigation control block diagram shown in Fig. 8. The updated position will also be send to the deployment ship for monitoring purpose. The swarm ASV should update the position of the AUV every certain period of time to avoid loss of tracking. In this case, ASVs have dual functions which are localizing the AUV and track the AUV as it moves. The position calculated by multilateration method as discussed earlier will be used for tracking the AUV. Compass will direct the ASV towards the AUV position in the close loop system.

This process will take place to guide the AUV to the docking station. This localization and tracking just take place in the global scope from docking system point of view. Once the AUVs are assisted close to the docking station, the positioning system is change from acoustic-based positioning to vision-based positioning (in local scope of the docking system). The detail of the procedure will be discussed in the next section.

C. *Advantages and Disadvantages*

The proposed method has advantages in term of flexibility, robustness and scalability as possess by the swarm robotic system. In addition, this method of localization could reduce operating cost, avoid extended human operator effort and able to cover large area of operation. It also introduces operation flexibly where area of operation could be expanded easily since the receivers are mobile and could tracks multiple underwater vehicles at the same time. It also requires minimum supervision because the receivers (swarm of ASVs) are autonomous and implanted swarm characteristics allow each of the ASVs to make appropriate decision such as move relative to the underwater vehicle position without the external intervention or instruction. The proposed method is expected to give a relatively accurate position as conventional method even though it is limited by the capability of the devices or components used in the system.

However, the proposed system requires a precise and accurate time measurement devices for accurate position estimation. Inaccurate time measurement will result in significant positioning error and inaccurate tracking. This system also needs a robust ASV system where it possibly maintains its position with minimum position error when affected by the external disturbances such as wave, current and weather changes. These issues are mostly related to the robust controller design, station keeping and appropriate ASV structural design to withstand the instabilities. In addition, this system requires a real time process which sometimes will cause delay in the process if the processor is slow for processing the signal. It also depends on the frequency of the data processing. However, for proof of concepts, acceptable low frequency data update is acceptable. The received signals will consist of coarse noise and other unwanted signals. To obtain accurate results extensive signal processing should be performed which sometimes will be challenging process especially when real time processing involves.

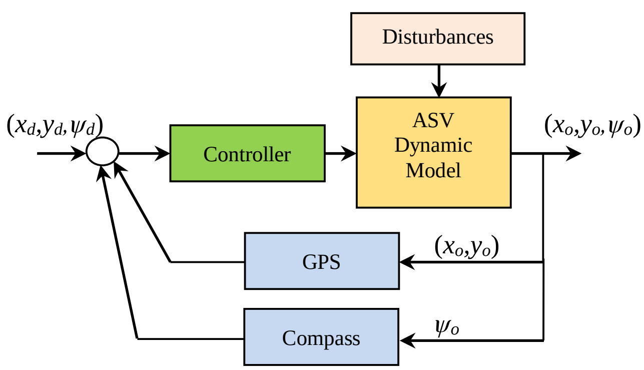


Fig. 8. Control block diagram of the ASV navigation

2.3 AUV Cooperative Navigation System

A proper navigation system for multiple AUVs is necessary to avoid loss of connection and to ensure the task could be performed efficiently. In addition, precise position of every AUVs are very important to maintain the AUV group formation and avoid collision between the AUVs. Therefore, each of the AUVs will compute their own position continuously using inertial navigation system. A strap down type of inertial navigation system which having the gyroscope and accelerometer sensor attached rigidly to the body of vehicle is used. The computational steps are shown below:

Step 1: A 3-axis accelerometer gives the acceleration in term of body frame, a^b

$$a^b = [a_x, a_y, a_z]^T \tag{3}$$

Step 2: A 3-axis gyroscopes gives the rotation speed of the body frame, ω

$$\omega = [\omega_x, \omega_y, \omega_z]^T \tag{4}$$

Step 3: Rotation speed obtained is used to compute the attitude of the body frame, R

$$R(t_n) = R(t_0) + \int \omega \, dt \tag{5}$$

Step 4: Then, acceleration in term of inertial frame, a is obtained.

$$a^i = Ra^b \tag{6}$$

Step 5: After that, velocity of the vehicle in term of inertial frame is calculated

$$v^i(t_n) = v^i(t_0) + \int a^i \, dt \tag{7}$$

Step 6: Finally, position of the vehicle in term of inertial frame is estimated

$$x^i(t_n) = x^i(t_0) + \int v^i \, dt \tag{8}$$

In this system, each of the AUVs will carry its own inertial navigation sensor and GPS. In our case, we limited our discussion for three AUVs navigation. Before submerge into the water (i.e. at the surface), all the three AUVs will record their initial position using GPS at the surface of the water. After submerge into the water, each of them will continuously run its inertial navigation system to estimate its position.

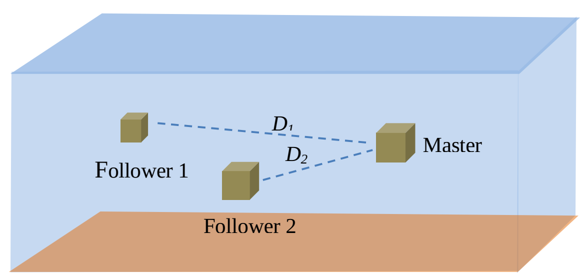


Fig. 9. Master-follower of the AUV

As discuss before, the lead AUV will obtain a high accuracy position from ASVs. The lead AUV (master) will synchronize with other two AUVs in order to help them achieve a higher accuracy of positioning system. The lead AUV will send its coordinate to other AUVs periodically by using acoustic modem. By calculating propagation delay of the acoustic signal send by lead AUV, the other two AUVs are able to calculate their distance from the master AUV as labeled by D_1 and D_2 in Fig. 9. Fig. 10 shows the position of the AUVs in the triangle formation where position of the slave is measured relative to the master position. This range information will be used to correct the position estimated by the inertial navigation system. The three AUV will follow their predefined path to the docking station as set by the ASV based on the location of the docking station. When the docking station is in sight of the camera, the vision system will be activated to guild the AUV go inside the docking station. The detail of the docking process in discussed in the next section.

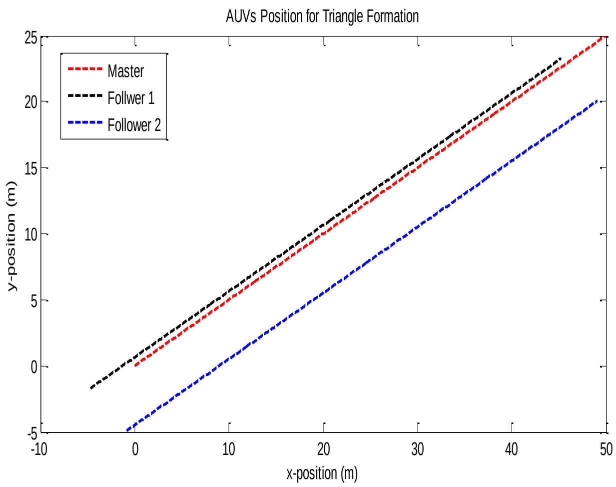


Fig. 10. Position of the AUVs in the triangle formation

III. Underwater Docking System

From the overall system operation, the docking process takes place only if there is requirement for battery recharging or data transfer. The docking process consists of four stages and each of them is described in the following subsections.

A. Stage 1: Power Status Monitoring System

A master AUV is programmed to monitor the power level of each and every AUV under its command periodically. In this paper, the power level and conditioning rule for docking of AUVs can be broken down into three rules. In the first rule, an AUV which has more than 20% of its total power does not need to be recharge. Then, in the second rule, if the master AUV detected a slave AUV which has power percentage in between 10% to 20%, the slave AUV is considered to be low on power and subjected to either needs or does not need to be recharge. Finally, in the third rule, an AUV which has less than 10% of its total power is in urgent need to be recharge right away. However, these rules are subjected to the power capacity of the battery being used to power the AUV and operation time. For example, 20% for high capacity battery can sustain longer operation compared to low capacity battery because the load i.e. power consumption is constant. Fig. 11 illustrates a master AUV currently monitoring the power level of each slave AUV denoted by S_1, S_2, and S_3.

B. Stage 2: Global Docking Procedure

Once the master AUV notices a slave AUV in direct needs for recharging, it will guide the slave AUV along with all second level powered AUVs towards an underwater docking station (UDS). This communication is realized through acoustic modem attached to each of the AUVs. The underwater docking station location information is provided and transmitted by surface vessels and further received by master AUV. Once the master AUV received the information, the guidance system will be like master AUV leads and slave AUVs will follow. In the meantime, other first level slave AUVs were left to continue to perform their tasks. Fig. 12 shows a master AUV leading slave AUVs S_2 and S_3 towards an underwater docking station, UDS using the information provided by the surface vessels.

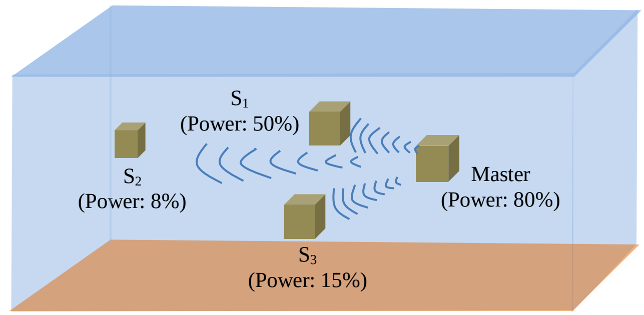


Fig. 11. Master AUV monitors slave AUVs' powers.

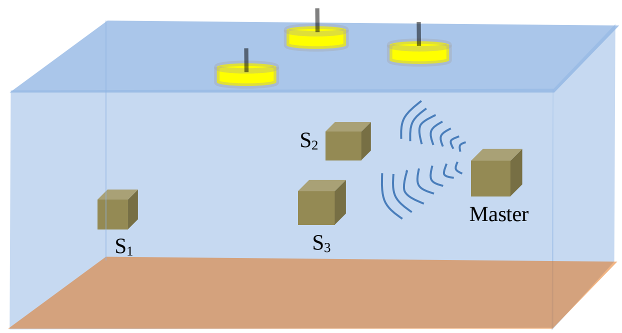


Fig. 12. Master AUV leading slave AUVs heading towards underwater docking station.

C. Stage 3: Local Docking Procedure

Once all of the AUVs had arrived at the underwater docking station site, they will dock systematically inside the station and subsequently recharges their batteries. This docking procedure is done optically using a camera mounted on the frontal side of each AUV. In order to locate the charging platform using the camera, there are several image processing steps to be performed and the function of each task is listed in Table I.

TABLE I
Samples of Times Roman Type Sizes and Styles

No.	Operation	Explanation
1	Image acquisition	An image of the entrance of the charging platform is captured using the camera. The aim is to capture all of the 5 lighting sources placed on the entrance
2	Color conversion	Converting the image from original red-green-blue (RGB) color channel to hue-saturation-value (HSV) color channel is important so as to make the light sources to be discriminated from the surrounding scene much easier
3	Color thresholding	Binarization by means of specific color is required with the purpose that only the interested color region which originates from the light sources is going to be processed
4	Morphological	Dilation followed by erosion are implemented

	operation	so that the light sources will become less noisy with black dotted pixels.
5	Circles feature detection	As the light sources projected resemblance to that of circular objects, Hough circle transform is used to extract these features.
6	Tracking	This task is important in sense that the AUV does not lose sight of the charging platform during homing and docking.

Fig. 13 illustrates the sequence of image processing tasks starting with using a camera device, followed by acquiring an image, converting color of the image, thresholding color of interest, morphological operation of dilation and erosion, circular shape detection, and ending with tracking of the light sources. For successful docking operation, the orientation of the AUV must align with the docking station according to the location of the lighting sources. The orientation error is then feed into feedback controller so that exact docking step could be achieved.

For further discussion, we assume that the underwater docking station can only accommodate one AUV at any given time. Therefore, least powered AUV is given topmost priority to dock inside the station and recharges its battery first. While waiting for the AUV to be fully recharged, the other AUVs will dock and wait inside a multi-level waiting platform. And while waiting in the platform, the AUVs will turn off all of its actuators as well as their sensors except their modem in order to conserve as much power as it can. The modem is turned on for communication purposes and awaiting their turn for recharging.

Once the least powered AUV is fully recharged, it will undock from the docking station and docks into the waiting platform. Consequently, another low powered AUV will undock from the waiting platform and starts docking into the station to power up its battery. This sequence will keep going on until all of the AUVs are fully recharged. Figure 8(a) illustrates by using vision, Master AUV M and slave AUV S3 dock inside multi-story waiting platform while slave AUV S2 docks inside the docking station. Figure 8(b) shows master AUV M and slave AUV S3 waiting for slave AUV S2 to be fully recharge.

D. Stage 4: Undocking Procedure and Mission Continuation

After all of the AUVs are fully recharged, the master AUV will instruct the entire slave AUVs to undock from the waiting platform. Next, the master AUV will guide the slave AUVs towards their last known mission location. Once they have arrived at the respective location, the master AUV will order slave AUVs to continue where they left from their previous missions. Figure 9(a) demonstrates AUVs undocked from waiting platform while Fig. 9(b) shows Master AUV M leading two fully charged slaves AUVs S2 and S3 back to their previous mission location.

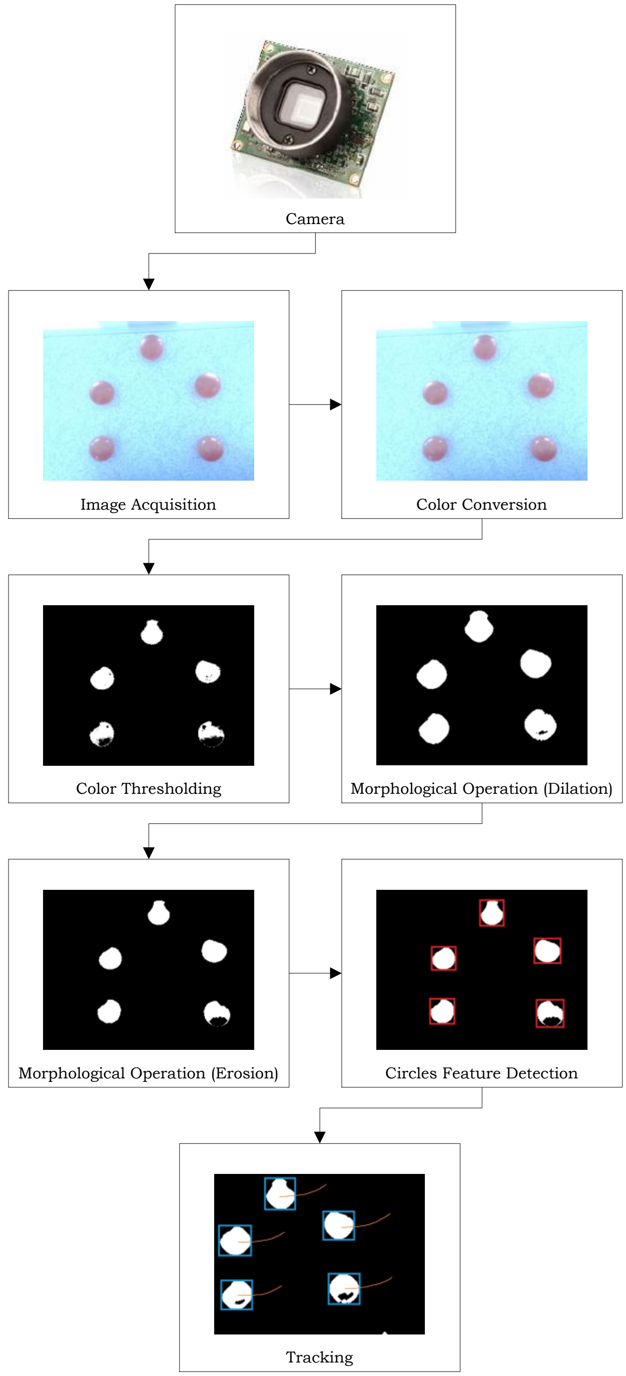
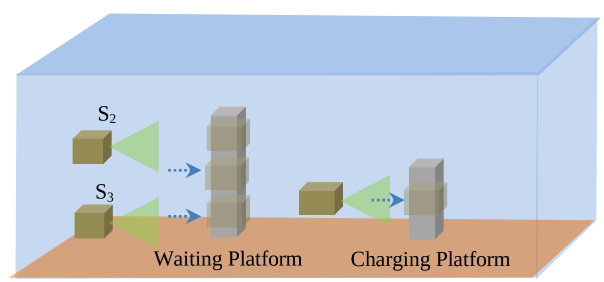
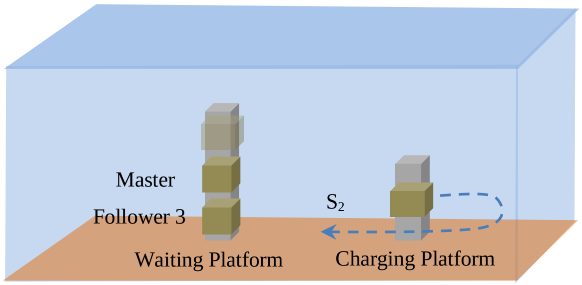


Fig. 13. Illustration of sequence of image processing task for underwater docking process

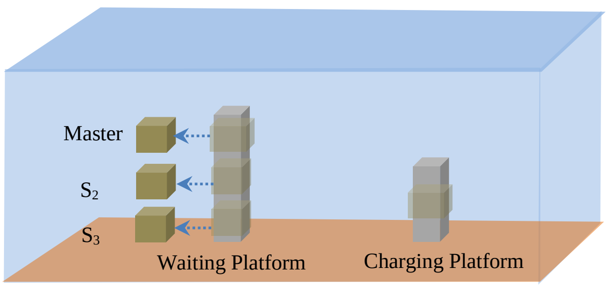


(a)

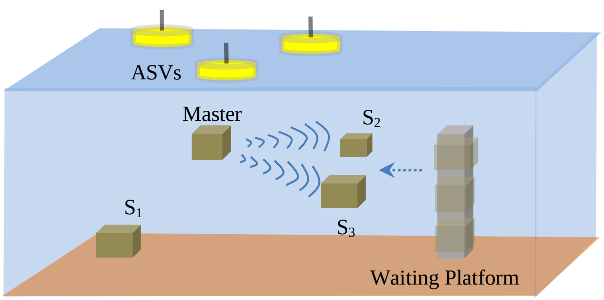


(b)

Fig. 14. Local docking procedure: (a) docking using vision, (b) two AUVs waiting for an AUV to be fully recharged.



(a)



(b)

Fig. 15. Undocking procedure (a) undocked from waiting platform (b) move toward mission site

IV. Conclusion

In this paper, a system framework for cooperative positioning of multiple AUV has been presented which includes cooperative localization using swarm robotics, cooperative navigation system for multiple AUVs and underwater docking system based on vision. It is expected that the proposed method of localization introduced more reliable and flexible underwater operation especially for docking operation. The proposed design allows us to develop separated sub-systems and finally combined them into a complete working system. This modular system design approach improves design flexibility for easy development, troubleshoot and maintenance. In the future, realizing this works required an extensive research work and multi-disciplines engineering and thus, a modular design for each system could be considered for easier system development.

V. Acknowledgement

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