Homing and Docking Algorithms for Circular Transmission and Receiver Arrays

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ABSTRACT

Homing and docking are two major components in the navigation of UAV's and UUV's. It involves the estimation of the six-element displacement vector based on the received signals, where three of the vector elements are associated with the translational displacement and the other three are for the rotation vector.

The homing procedure is based on the estimation of the rotation vector with far-field approximations. In the docking range, the displacement estimation becomes more sensitive and critical. Far-field approximation-based algorithms are no longer effective, and high-precision techniques become important and need to be developed.

In this paper, we examine and model the multi-dimensional displacement estimation for circular arrays. It allows us to accurately assess the performance as well as the limitation of the algorithms, with respect to various system parameters such as the size of the arrays, range distance, transmitted waveforms, and signal processing algorithms.

INTRODUCTION

Remote sensing and guidance for Unmanned Autonomous Vehicles (UAVs) is a critical component for the navigation and controls systems necessary for operation. In the research and design of advanced controls systems for UAVs, its often assumed that high quality navigation, as provided by the Global Position System (GPS), is available to deliver robust and accurate positioning data. With accurate position information, control and robotics systems have improved significantly and become completely automated without the need for manual guidance or intervention. UAV systems will navigate over far distances along a set of way-points autonomously and adapt to obstacles along the way. One task that remains difficult to automate, however, is precision homing and docking of UAVs with its respective base station. In cases where high quality position data is not available, such as GPS-denied environments, this task becomes intractable. Further research is needed in remote tracking to support high-precision navigation tasks like homing and docking [1-4].

Current solutions for remote navigation of UAVs include Inertial Measurement Units (IMUs) and optical navigation systems, which have proved to be effective in many situations. Commercial IMUs are available that can provide accuracy comparable to GPS tracking over short time periods. Recent advances in Simultaneous Localization and Mapping (SLAM) camera systems have also been successful in allowing UAV systems to navigate complex and obstacle burdened scenes. However, without fiducial geo-spatial markers both systems tend to suffer long-term error accumulation effects and limit the overall precision. For the homing and docking task, where positioning of both the docking platform and the UAV is required to be known to high accuracy, the accumulated position error can leave these solutions undesirable and, in some cases, unusable. As a result, in this paper we propose a cooperative navigation and tracking system, with circular acoustic transceiver arrays based on both the docking platform and UAV.

The motivations for this work stemmed from past efforts on designing automated navigation procedures for Unmanned Underwater Vehicles (UUVs) [5,6]. The UUVs concept of operation consisted of autonomously completing a surveillance mission, and upon returning to its home base station, it required manual piloting to complete the more complicated docking procedure. To conserve pilot time and communication bandwidth, it would be beneficial if the approach and docking of the UUV with the home base was completely automated. A conceptual diagram of this scenario can be seen in Fig. 1. The underwater environment imposes very low-power and size constraints on any tracking system to be integrated with the UUV, as well as restricted the use of optical and GPS tracking systems. To operate in these requirements, our proposed system operates in the acoustic modality to implement the tracking system.

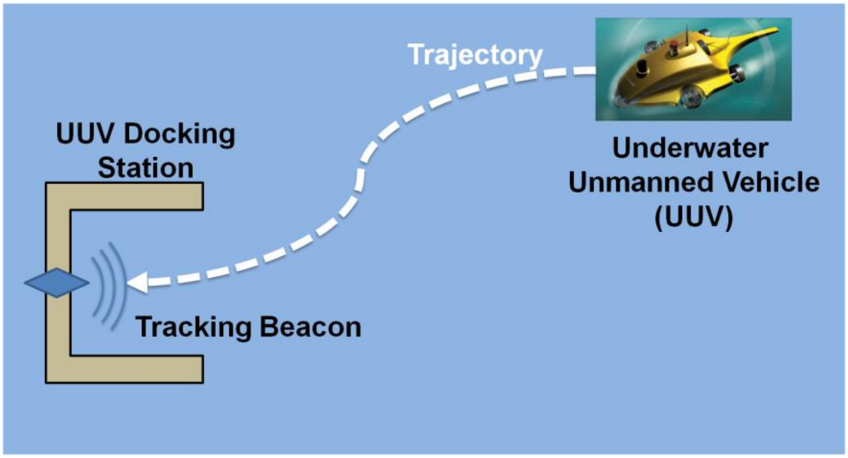


Figure 1. UUV homing and docking conceptual diagram

The homing-docking procedures in UUV navigation involve three key components. The first is the estimation of the bearing angle in the far field for the homing process. The second component is dynamic path planning for the optimal approach. As the UUV reaches the near field, the docking procedure is then activated, as the third and final task. For this work, we will review bearing angle estimation procedure with circular acoustic transceiver arrays and introduce the sensing and tracking approach during the docking phase. Specifically, the tracking system will focus on estimating the angular position of the UUV, which can be used by the controls system to autonomously complete the task. A system overview will be presented in the following sections, as well as mathematical analysis and numerical results to support these claims.

ACOUSTIC NAVIGATION SYSTEM

The navigation system proposed here is comprised of a dual acoustic transceiver array, where the transmit array resides on the docking station and the receiver on the UUV. The transmit array emits an active acoustic signal that the UUV can acquire and use to navigate safely back to the docking station. The acoustic modality is chosen due to its propagation characteristics in water and conventional availability in underwater sensor systems. Due to the unmanned nature of the vehicle, it is critical that the navigation system be of low complexity and power.

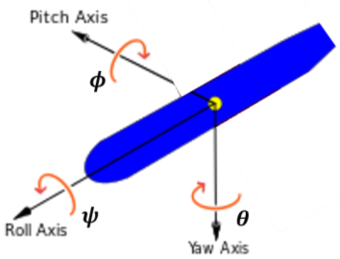
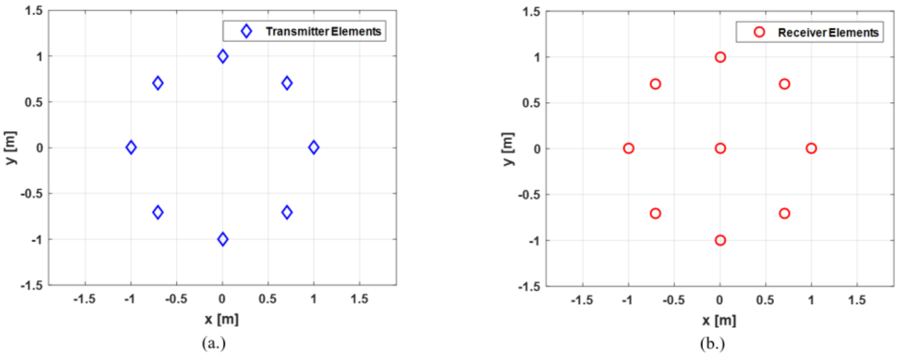


Figure 2. Angular Rotations of UUV upon Approach

The control objective for the UUV is autonomous maneuvering into the base station from a far distance and safe docking in a controlled manner. For this task, the UUV does not need to determine its absolute geolocation, and instead only needs its *relative position* with respect to the dock. Furthermore, the key position parameter to determine is its *relative angular position*, which can be defined in terms of its yaw, pitch, and roll angles as $\boldsymbol{p} = [\theta,\ \ \phi,\ \ \psi]$ with respect to the base station. This parameter can be seen in Fig. 2 and reducing the navigation task to estimation of the angular position vector allows for implementation of an acoustic transceiver system with minimal bandwidth requirements.

The two main design components of the acoustic transceiver system are the array geometry and waveform design. The transmit and receive array geometries proposed here can be seen in Fig. 3. The transmit array will be comprised of *N* acoustic transducer elements arranged in a circular manner, and the receiver will also be designed as a circular array with an additional receive element in the center. Circular arrays provide sufficient spatial coverage for the UUV to estimate its angular position. The symmetrical properties of the arrays can also be exploited for computationally efficient techniques for parameter estimation, which allows for a low complexity design that will not overburden the UUV and impede operation.



(a.)
(b.)

Figure 3. *N=8* element acoustic transmit array (a.) and receive array (b.)

The waveform design for the transmit array will be based exclusively on a Continuous-Wave (CW), single frequency format. Due to the requirement for relative angular position, low bandwidth CW signaling provides sufficient navigation information to the UUV for homing while limiting the overall system complexity. The transmit and receive arrays will operate in full quadrature, as a dynamic phased array with appropriate array factor weighting for parameter estimation. The critical feature of operation here for transmission and receive signaling will be the splitting of the task into two separate tasks: homing and docking operations. Both schemes will utilize the same transceiver array, but with different signaling requirements as will be discussed in the following sections.

HOMING OPERATION

The homing operation is the first stage of the navigation task, where the primary objective of the sensor system is to estimate the relative bearing angle of the UUV with respect to the transmitting homing station. The UUV's receiver array must detect and record the transmitting beacon signal, and from only this measurement estimate its relative bearing for full autonomous navigation. From the bearing angle estimate, the yaw and pitch angles can be determined, and the appropriate heading can be achieved by the controls system. It's important the estimate be computed in a real-time manner to ensure adequate response and navigation of the UUV.

The phased array transmission and receive design for the homing operation requires all transmitter elements emit an acoustic CW signal with appropriate phase shifting, and the receiver simultaneously records all transmit signals. For the homing stage, the receiver array only requires activating the center receiver element. From the quadrature measurement at the center receiver element, the superposition of all transmit signals is recorded and from the accumulated phase difference between each signal the relative bearing angle can be determined. Optimal estimation of the bearing angle parameter from phased-transmit arrays and single element receiver elements has been investigated extensively in prior work [7,8]. Here we present a short summary of the results, where in Fig. 3 the estimation accuracy vs. SNR is displayed.

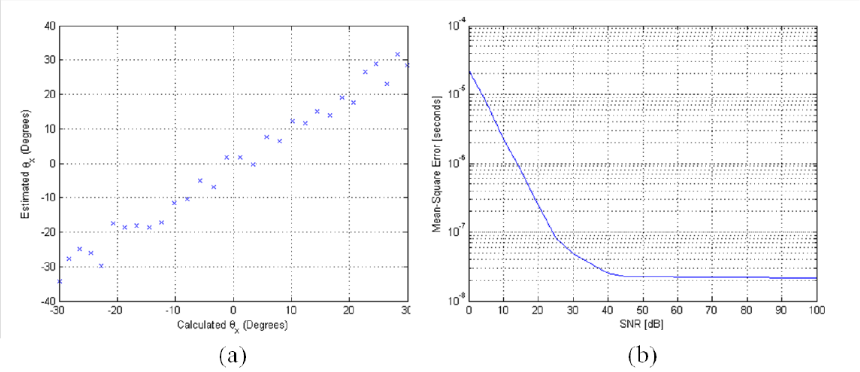


Figure 4. (a) Bearing Angle Estimation Results and (b) Performance vs. SNR

The homing operation will continue until the UUV successfully aligns in bearing within sufficient precision of the angle estimation procedure. Once the bearing is aligned, the docking operation for the UUV will engage as explained in more detail in the next section.

DOCKING OPERATION

Upon successful homing, the UUV will be completely aligned in bearing and the docking operation can begin. With the bearing angle successfully aligned in $\theta,\ \ \phi$, the only remaining task is to estimate the roll angle offset of the UUV with respect to the docking station. Given the array configurations this is equivalent to estimating relative roll angle offset of the circular transmitter array with respect to the receiver array. Once the arrays are aligned the UUV can dock with the base station to complete its mission.

The array signaling configuration for the docking mode is similar to the homing mode, however, the receiver will implement a modified estimation procedure to compute its roll angle offset relative to the transmit array. For this mode, all the transmit elements in the array will emit a single frequency homing signal. The central receive element will actively record the beacon signals, and in addition all the circular receiving elements will also actively measure the beacon signals again in full quadrature with appropriate phased array weighting. From these multiple measurements, the roll offset can be estimated using the mathematical model presented here.

Firstly, the base transmit signal to be emitted is the CW single frequency waveform, which can be expressed mathematically as:

$$s(t) = \exp(2\,\pi\,f_0\,t)$$

Each *nth* transmit element will phase shift this signal by its corresponding angular position of its array geometry, and emit a CW signal of the form

$$s_n(t) = \ \exp(2\,\pi\,f_0\,t)\ \exp\left(j\,2\,\pi\frac{n}{N}\right)$$

and each *mth* receiver will measure a delayed superposition of all transmit signals as

$$r_m(t) = \left(\sum_{n=1}^{N} s_n(t - t_{nm})\ \ \exp\left(j\,2\,\pi\frac{n}{N}\right)\right)$$

where t_{nm} and d_{nm} are the propagation delay and propagation distance from the *nth* transmitter to the *mth* receiver. This delay information will provide the critical measurement for estimation of the roll angle ψ.

For two circular transceivers arrays each with a radius *R* and separated in range by a distance *D*, it can be shown that the propagation distance between the *nth* transmitter and the *mth* receiver will be expressed in terms of the roll offset as

$$d_{nm} = t_{nm}\ \cdot c_p\ = \left[2\,R^2\,\left(1 - cos\left(\psi + (n + m - 2)\ \frac{2\pi}{N}\right)\right) + D^2\right]^{\frac{1}{2}}\ for\ n \neq 0$$

It is important to note that *n=0* corresponds to the center receiver element in the array, which can not acquire any roll offset information.

From the receive signals, a new intermediary signal can be defined as the sum of each receiver signal weighted by the conjugate of their angular position in complex form. For example, the $n=1$ and $m=1$ transmitter and receiver elements have an angular position of 0 degrees. The weighted sum can then be demodulated by the received signal from the center element to properly account for the mean propagation distance. This intermediary signal is then defined as

$$\begin{aligned}\rho(t) &= \left(\sum_{m=1}^{N} r_m(t) \exp\left(-j \frac{2\pi}{N}\, m\right) \right) \cdot r_0^*\,(t) \\ &= \left(\sum_{m=1}^{N} \left(\sum_{n=1}^{N} s_n(t - t_{nm})\ \exp\left(j\, 2\, \pi \frac{n}{N}\right)\right) \exp\left(-j \frac{2\pi}{N}\, m\right) \right) \cdot r_0^*\,(t) \\ &\approx \frac{1}{N} \sum_{n=1}^{N} \exp\left(\, j\, \beta\, cos\left(\, \psi + n \frac{2\pi}{N}\right)\right) \exp\left(j\, n \frac{2\,\pi}{N}\right)\end{aligned}$$

The approximation is valid at distances greater than the wavelength of the propagation signal, which would be the case for most realistic scenarios. It can be seen that the roll offset is entirely present in the phase component of the demodulated signal scaled by a constant phase factor β which depends on the temporal frequency and propagation distance. This parameter will be normalized by calculating the phase argument of the summed signal, and the final roll parameter estimate can be computed as

$$\hat{\psi}(t) \approx \arg\{\, \rho(t)\, \}$$

The estimate over time can then be fed into the controls system until the roll alignment is achieved with sufficient precision.

A numerical simulation for the algorithm was performed to validate the approximation used in the estimation procedure. The physical parameters for the simulation were set to have a transceiver array radius of $R=1m$, $N=8$ elements, at a distance of $D=25m$, and a CW frequency of $f_0 = 150Hz$ in an underwater ocean environment. The roll estimate vs. actual roll position can be seen plotted in Fig. 4, where the estimate visibly tracks the actual roll position very closely with a small bias offset of approximately 5 degrees. This bias offset can be attributable to the approximation error in the estimation procedure but can potentially be calibrated out in a deployed system. Overall, the roll angle estimation tracking shows strong promise as an efficient navigation system for automated docking procedures for UUVs.

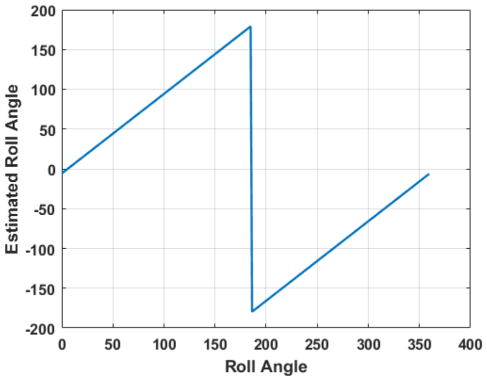


Figure 5. Roll Angle Offset Estimation Results

CONCLUSIONS

This paper presents an overview of an acoustic navigation system for UUV homing and docking tasks. The navigation problem was reduced to the estimation of the bearing and roll angle offsets of the UUV with respect to the docking station, and a computational efficient estimation procedure was presented as a solution. The solution showed strong accuracy in both bearing and roll estimation to be a tractable system for navigation and was implemented with the goal of low complexity to reduce size and power requirements of the UUV. Analysis and numerical simulations were presented supporting the accuracy of the methods as well. Future work, will involve system operation of the design parameters here, and integration of the navigation and controls systems for full-system analysis.

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