Proceedings of the 8th IFAC International Conference on
Manoeuvring and Control of Marine Craft
September 16-18, 2009, Guarujá (SP), Brazil

Relative positioning of multiple underwater vehicles in the GREX project

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Abstract: This paper discusses the estimation of relative positions of a swarm of autonomous underwater or surface vehicles. The solution of this problem is crucial for performing a coordinated path following in a spatial formation. It forms a necessary prerequisite for establishing a coordinated control behavior of multiple vehicles which is the major goal of the European Project GREX. It is shown that the relative positioning problem is solvable when dead reckoning data are combined with the mutual range data measured via acoustic modems. Therefore, the limited capability of the acoustic communication channel has to be considered when developing a solution algorithm. A simple concept is achieved by implementing a recursive variant of a trilateration technique by means of an extended Kalman filter.

Keywords: Include Multiple AUVs, Coordinated Navigation, Trilateration.

1. INTRODUCTION

The positioning problem for multiple underwater vehicles, seen from the viewpoints of coordinated control and from underwater communication, shows some new aspects compared to the positioning problem of a single vehicle. While failures or poor performance of the navigation system of a single vehicle normally do not lead to a malfunction or damage of other subsystems, the consequences for the multiple vehicle case can be more serious. A large error in the estimation of the relative position of the agents can cause collisions or divergence of the group, the latter leading to a temporary or ultimate break off of the data connection and thus, possibly to a loss of individual members of the group. These observations suggest defining the following two sub-problems of the positioning problem for multiple underwater vehicles.

Absolute positioning defines the task of determining the position of each individual vehicle in an earth fixed frame using navigation data of the distributed AUV sensor network.

Relative positioning comprises the task of determining the mutual relative positions of the group members, using navigation data of the distributed AUV sensor network. In most of existing projects dealing with multiple AUVs, the usage of an acoustic positioning system, such as LBL or USBL is proposed for this purpose, see e.g. (Cruz et al, 2003) or (Cuff and Wall). However, the application of acoustic tracking systems calls for large operational effort (in case of LBL) or makes the presence of some surface vessel (in case of USBL) necessary. Furthermore, they are in general quite expensive systems. For single vehicles, in many cases, a high performance dead reckoning system suffices for a multitude of possible applications. Due to their inherent error drift, they can however not be used for coordinated navigation of multiple AUVs– more precisely, for the relative positioning task.

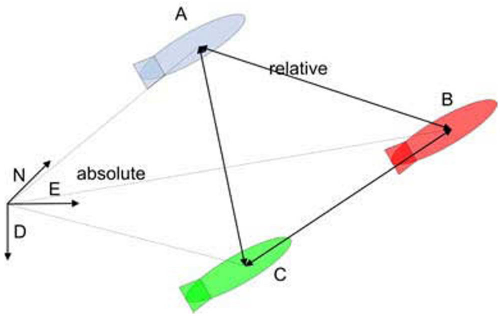

Fig. 1: Absolute and relative positioning

The aim of this paper is to propose a method, by which relative positioning is possible by means of merely

- a dead reckoning navigation system on each vehicle of the group.
- a communication system which is able to distribute information in the AUV network (via acoustic modems).
- a device, to be implemented on each vehicle, which is capable of performing mutual range measurements (usually the same acoustic modems).

978-3-902661-51-7/09/$20.00 © 2009 IFAC

10.3182/20090916-3-BR-3001.0063

2. THE BASIC PRINCIPLE

The general arrangement consists of a number N of underwater vehicles, each of them is assumed to be equipped with a full navigation system, computing at least the following quantities continuously:

- position in navigation frame (Latitude, longitude, depth, additionally altitude),
- velocities in local level frame (north, east, down),
- Euler angles (Roll, pitch, heading),
- angular rates in body frame,

The minimum amount of sensors consists of a heading sensor (in form of a magnetic compass) and a velocity sensor (e. g. Doppler velocity log or impeller log) to provide dead reckoning functionality. The navigation accuracy achieved by AUVs, range from some few meters per hour (high performance INS/DVL combinations) down to more than hundred meters per hour (low cost compass/velocity sensor combinations).

Each individual navigation system is assumed to be initialized independently, normally by means of a GPS fix after launch, while still remaining at the surface. It is also assumed that the system clocks on the vehicles are being synchronized during that mission stage, e.g. by using the GPS-PPS signal. The position errors of this initialization procedure will show some correlation, since some GPS error sources, such as atmospheric disturbances, affect each single GPS receiver in the same way. But it can be assumed, that the individual position errors are becoming statistically independent after some time soon after submerging.

In the scope of the GREX project each member vehicle is equipped with an acoustic modem and a processing unit, on which the team functionalities are implemented.

The GREX navigation module receives input data from the proprietary navigation system of the respective vehicle on the one hand and estimates of other vehicle, broadcasting their navigation solution via the acoustic modem on the other hand. In the scope of this paper there are no special assumptions about the network topology, protocols, etc. It is assumed that the GREX navigation module on vehicle A receives from time to time data from some other vehicle, say B. The origin of a data set will always be known to the receiving vehicle by an ID contained in the header of the received data. The method for relative positioning, proposed here, only processes data originating from different vehicles independently. Thus, we can restrict ourselves to the special case of only two vehicles exchanging data. In the case of N vehicles, each navigation module runs N-1 instances of the algorithm described below, independently.

Without an absolute position aiding, the individual position errors will show some drift behaviour, due to uncompensated errors in the dead reckoning navigation systems of the vehicle navigation systems. As a consequence, the information available to each vehicle has to be enhanced. The least demanding type of additional measurements for relative position aiding, from a hardware point of view, consists in the determination of ranges between vehicles. Many acoustic modems on the market are capable to do range measurements when establishing a connection between two stations. This is done by measuring round trip time of flight of a pulse signal, emitted by one and received by a second modem which in turn retransmits the pulse signal. The draw-back of this method is that one vehicle can exchange range data with not more than one other modem at the same time.

An interesting alternative is the determination of one-way travel time of a pulse, emitted by a specific vehicle. The advantage is that all vehicles of the group may determine the range to the emitting vehicle to the same time. The time of the emission of the pulse has to be known to all other vehicles, either by sending it via the transmission channel, or alternatively by scheduling the emission times prior to the mission. The latter concept is used and discussed in-depth e.g. in (Martins *et al.* 2003) and in (Willcox *et al.* 2006). The receiving vehicles determine the time of interrogation of the pulse, and, from that, compute its time of flight and from this the range between emitting and receiving station. For this method, very precise time synchronisation and low-drift clocks have to be implemented.

In the subsequent considerations we will not refer to any special method of determining ranges and exchanging dead reckoning navigation data between two vehicles. Instead we will make the following general assumptions:

Two vehicles A and B determine their range $r^{AB}(t_k^{AB})$ at time t_k^{AB}, k denoting the index of the k-th connection between the modems on A and B.

Furthermore, A and B exchange their individual dead reckoning position data, valid also at time t_k^{AB}. We denote by $p_{DR}^A(t_k^{AB}) = [x_{DR}^A(t_k^{AB}), y_{DR}^A(t_k^{AB}), z_{DR}^A(t_k^{AB})]^T$ the position estimate of vehicle A's own dead reckoning navigation system, valid at the connection time t_k^{AB}.

Notice that the data $r^{AB}(t_k^{AB})$ and $p_{DR}^A(t_k^{AB})$ will be known to vehicle B considerably after time t_k^{AB}, due to unavoidable time delays in the underwater communication network. However, to keep the presentation traceable, we make the idealized assumption that the time needed to transmit navigation data is negligible. For a rigorous treatment and real time implementation, time delays have been considered, see e.g. (Larsen *et al.* 1998).

The basic concept for the solution of the relative positioning problem is illustrated in fig. 2 for the two-dimensional case. It is based on the idea that a set of distances can be generated from the real measurements which geometrically determine the relative position of vehicle B to vehicle A uniquely by trilateration. In view of fig. 2, these distances are the range observations of three consecutive modem connections, r_1^{AB}, r_2^{AB}, r_3^{AB}, the position differences Δp_{12}^A, Δp_{12}^A for vehicle