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Kalman Filter Based Team Navigation for Multiple Unmanned Marine Vehicles

Matthias Schneider, Thomas Glotzbach, Marco Jacobi, Fabian Müller, Mike Eichhorn, and Peter Otto

***Abstract*—In applications employing Multiple Unmanned Marine Vehicles (MUMVs), the navigation has a very great importance to guarantee formation preservation and collision avoidance. While single vehicles usually base their navigation on absolute measurements (GPS, inertial navigation) to determine their position relative to the world, it may be reasonable to perform a relative navigation within vehicle teams. In this paper, we propose relative team navigation based on Kalman Filters to enable a velocity controller to establish a close formation under the typical marine constraints (narrow band width communication with low reliability). We will simulate a team of three marine vehicles and compare the results of different strategies for team navigation.**

I. Introduction

THE realization of Multiple Unmanned Marine Vehicles has a growing importance in the research on Marine Robotics. In the European Research Project 'GREX', in which framework this work was performed, it is aimed to realize several mission scenarios that require a direct cooperation between several heterogeneous marine surface and underwater vehicles. One possible application that will be realized in this project is the Marine Habitat Mapping (Fig. 1). A surface craft and an underwater vehicle are linked by cable and perform a cooperated lawnmower maneuver to scan a certain area. Pictures and data will be collected by the underwater vehicle and sent via cable and radio link to a supply ship where marine biologists can watch the data online. In case of an interesting situation, they can employ one of the other underwater vehicles waiting in stand-by to move to the area of interest and collect more data, while the two linked vehicles continue their mission.

This mission, among others, shows the need for cooperated behavior of marine vehicles. An important aspect is the capability of mission planning to supply all vehicles with an adequate plan. This minimizes the needs for online adaptation which is always limited by the constraints of underwater communication. For a cooperated lawnmower, the real course can be planned for each vehicle, consisting of straight lines and arcs [1]. Therefore, the control task is to adapt the vehicle velocities to keep a close formation, which means to realize an equal Degree of Execution of the current track for each vehicle.

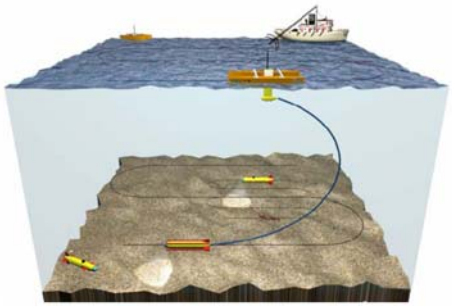

Fig. 1. Marine Habitat Mapping

The navigation of the vehicles is the important base to determine the current Degree of Execution. Of course each vehicle must know both its own position and the relative position of other vehicles to calculate the deviation of the planned path. We assume each vehicle is able to determine its own position with sufficient accuracy. Surface crafts may use Differential GPS, while underwater vehicles can use several methods based on inertial navigation. In the current research, there are several methods to deal with the typical increasing navigation error with inertial measurements and guarantee a sufficient accuracy for several hours (see [2], for instance). Problematically, the acoustic communication link between the vehicles is not sufficient to supply all vehicles at all time with all positions of the team mates. Furthermore, several vehicles may not communicate at the same time. There is the need for a communication management that deals with this problem. Nevertheless, according to first tests within the GREX-project, the delivery of a single message from one vehicle may take 10 to 20 seconds. Even in small groups, that means that a vehicle may get navigation data from a certain team mate not more often than one time per minute, which is too less for an appropriate control algorithm. Moreover, when the message with a position of a vehicle reaches another one, the transmitting vehicle has already moved, and the position is no longer valid.

There are several possibilities to deal with this problem. To guarantee close formations, it may not be necessary to monitor the links between each pair of vehicles. According

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Matthias Schneider, Thomas Glotzbach, Marco Jacobi, Mike Eichhorn, and Peter Otto are with the Institute for Automation and Systems Engineering at the Technische Universität Ilmenau, P.O.Box 10 05 65, D-98684 Ilmenau, Germany (phone: +49 3677 69 1416; fax: +49 3677 69 1434; email: {schneider.matthias, thomas.glotzbach, marco.jacobi, mike.eichhorn, peter.otto}@tu-ilmenau.de)

Fabian Müller and Thomas Glotzbach are with the Fraunhofer Application Center System Technology (AST), Am Vogelherd 50, D-98693 Ilmenau, Germany; (e-mail: {fabian.mueller, thomas.glotzbach} @ast.iitb.fraunhofer.de)

to the chosen formation topology, it may be enough to control the distance and adjustment between single pairs of vehicles, like it was suggested in [3]. In the presented scenario, even those simplifications may not be enough to establish a standard controller with sampling times of roughly one second. It is therefore necessary to employ special methods beyond the scope of a simple control scheme to solve this problem.

The usage of an estimator system is an appropriate solution to provide the controller with sufficient data between the messages containing the current positions. Reference [4] proposes a navigation system based on the distance measurements between the vehicles, measured by communication modems. For this solution modems need to be employ that are able to determine the distance between transmitter and receiver. If it is not intended to use those (usually expensive) modems, the absolute position measurements of each vehicle can be used as a base, as long as navigation systems with high accuracies are used (see above). We showed the basic idea in [5], and will expand this approach now to prove its eligibility for formation preservation of marine vehicles in a coordinated maneuver. In [5], we described the idea of a localization estimation observer for one vehicle from a stationary base. In this paper, we use this approach as a solution for the described control problem. We will discuss a scenario where several vehicles have to keep a close formation under limited communication possibilities. It will be shown, that it is possible to use the strategy presented in [5] for a closed loop control. In chapter 2, we will discuss the control algorithm we adopted from literature and develop our quality criterion which we are going to use in the simulation in chapter 5. Chapter 3 gives a short overview on the software simulator we use for the simulations. The estimator concept is explained in chapter 4, before we describe the performed simulations and discuss their results in chapter 5.

II. ALGORITHMS FOR FORMATION PRESERVATION AND EVALUATION

A. Degree of Execution and control algorithm

If several vehicles have to run a cooperative maneuver in a close formation, their velocities need to be adapted in order to keep the formation deviation small. This is valid for each single movement maneuver (track), both straight lines and arcs. For lines, the foot of perpendicular of the current (time step k) vehicle m's position on the desired track λ is calculated and used to determine the Cross Track Error, $XTE_m(k)$, and the current position on the track, $d_{m,\lambda}(k)$ (Fig. 2). For vehicles on parallel tracks, it can be stated that the controller need to guarantee that the value for $d_{m,\lambda}(k)$ is equal for all vehicles.

For arcs, the situation is similar. The cross track error $XTE_m(k)$ is the difference of the distance 'Center Point – vehicle position', subtracted by the radius. Instead of the

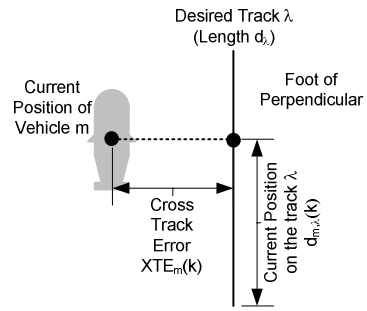

Fig. 2. Basic definitions for track following

current position on the track, the current angle $\varphi_{m,\lambda}(k)$ between the lines 'Center Point – start of the track' and 'Center Point – vehicle position' is used which can be calculated using arc tangent. In order to use the same controller for both lines and arcs, the value 'Degree of Execution' Θ is introduced as the quotient of current position $d_{m,\lambda}(k)$ by length of the whole track d_λ or of the current angle $\varphi_{m,\lambda}(k)$ by the whole angle φ_λ. This value rises from 0 to 1 in each single track.

$$\Theta_m(k) = \frac{d_{m,\lambda}(k)}{d_\lambda} \quad \text{or} \quad \Theta_m(k) = \frac{\varphi_{m,\lambda}(k)}{\varphi_\lambda} \tag{1}$$

The controller has the task to equalize the values of Θ for all vehicles within one time step by calculating new velocity values $v_{m,\lambda}(k)$ for each vehicle. The idea of this concept was suggested in [6]: Based on a P-controller concept, the differences of all other vehicles' Θ with the own Θ are multiplied by an individual gain and added to the desired speed of the mission plan $v'_{m,\lambda}(k)$ that already includes effects like different track lengths in cooperated arcs. For p vehicles, the new velocity $v_{m,\lambda}(k)$ for each vehicle to correct the formation deviation is

$$v_{m,\lambda}(k) = v'_{m,\lambda}(k) + \sum_{i=1}^{p,\neq m} K_i\left(\Theta_i(k) - \Theta_m(k)\right). \tag{2}$$

Of course, the velocity is limited for each vehicle by a maximum value. To reach a controllable behavior and guarantee for the ability of keeping a claimed depth, there may also be a minimum velocity limit.

It can be stated that the controller has the task to minimize the quality criterion Q_m which is defined as

$$\forall m \; Q_m = \sum_{i=1}^{p,\neq m} \Delta\Theta_{im}(k) = \sum_{i=1}^{p,\neq m}\left(\Theta_i(k) - \Theta_m(k)\right). \tag{3}$$

B. Measurement of the Formation Deviation

Whenever mobile systems on a coordinated lawnmower have the task to measure data that shall be merged together afterwards, it is important to keep the desired formation. The quality of the formation needs to be calculated in every time step and added over the mission time to judge the employed procedure. Let FD be the general value of the Formation Deviation, $fd(k)$ the value of the kth of l steps with a step size of T. Then FD is defined as

$$FD = \frac{T}{l}\sum_{k=1}^{l} fd(k). \tag{4}$$

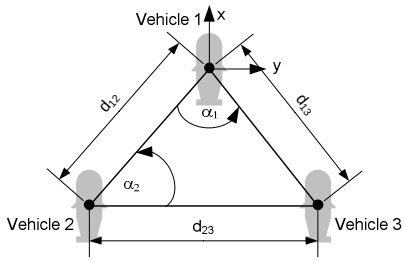

Fig. 3. Description of formation

For the definition of the Formation Deviation term in a single time step, we use a formation description like depicted in Fig. 3. The orientation of axes follows the NED coordinate system [7]. The adjustment of the vehicles is described by the angle α_m for vehicle m of p. This is the angle between the vectors from vehicle m to $m-1$ and to $m+1$ respectively. It is postulated that the vehicle numeration is done that way that there are no intersections between these lines to the proximate neighbors (formation pattern as n-polygon). Each n-polygon is described by $n-1$ angles, so one of the vehicles need not to be checked. The link between every vehicle and its follower $(m,m+1)$ is described by the distance $d_{m,m+1}$. These bondings will be checked within every time step of the simulation. Based on the position results it is possible to calculate the current values $d_{m,m+1}(k)$ and $\alpha_m(k)$. Also, the cross track error $XTE_m(k)$ of the vehicles may be used to describe the quality of formation, as a formation which is quite intact, but far away from their set track may also deliver bad results. The user may have the possibility to weight the influence of the three criteria distance, angle and cross track error, setting the weighting factor ξ_1, ξ_2 and ξ_3 in the array between 0 and 1. The Formation Deviation at time step k is:

$$fd(k) = \xi_1 \cdot \frac{1}{p} \cdot \left[\left(\left| d_{1p} - d_{1p}(k) \right| \right) + \sum_{i=1}^{p-1} \left(\left| d_{i(i+1)} - d_{i(i+1)}(k) \right| \right) \right] \quad (5)$$
$$+ \xi_2 \cdot \frac{1}{p-1} \cdot \sum_{i=1}^{p-1} \left| \alpha_i - \alpha_i(k) \right| + \xi_3 \cdot \frac{1}{p} \cdot \sum_{i=1}^{p} XTE_i(k)$$

The real distance can easily be calculated from the real positions of two vehicles, using the Theorem of Pythagoras. The angle between the two lines of three vehicles can be calculated using the scalar product, where the lines are interpreted as vectors.

III. HIGH LEVEL SIMULATOR FOR MUMVS

To model the controlled behavior of the different vehicle types, which are used in the project GREX, a simplistic kinematical model was designed. We demonstrated the basis ideas in [8]. This model allows both a simple and a realistic simulation of the complex behavior of the autopilot and the vehicle dynamics. In this case, only the control loop behavior of the vehicle states roll, pitch, heading and surge will be reproduced using a time delay model. Fig. 4 illustrates the hierarchical model structure for the controlled vehicle behavior. Fig. 5 shows the realization of the four control

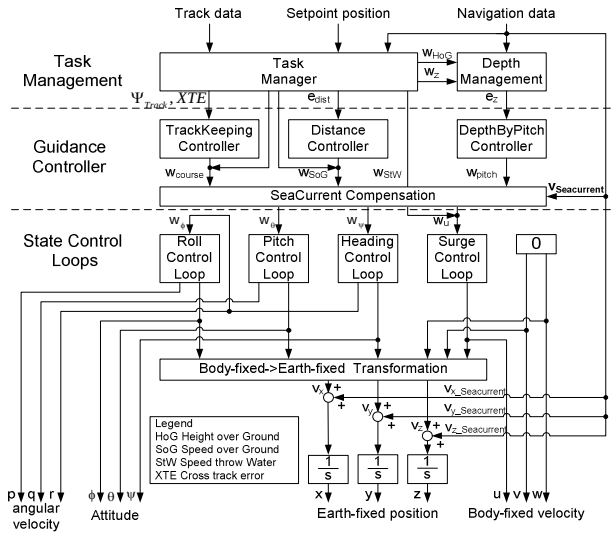

Fig. 4. Structure of the controlled vehicle behavior model

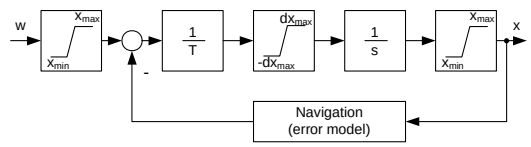

Fig. 5. Design of the control loops as first order lag elements

loops (roll, pitch, heading, surge) as first order lag element with the possibility to consider limitations in the absolute values (e.g. velocity) and their derivation (e.g. acceleration) as well as an navigation error model (fixed offset, white noise and continuously increasing error due to inertial navigation).

Models for guidance tasks like the depth, track keeping and distance controllers work in combination with an algorithm to compensate for the influence of the sea current. This is possible by using known sea current vector $v_{Seacurrent}$ and allows a simple control design for the guidance controllers (only P-controllers). The block SeaCurrent Compensation converts the desired set point values like course w_{course}, pitch angle w_{pitch} or speed over ground w_{SoG} (in which $v^0_{veh\_ef}$ is a unit vector into the desired direction) into the effective set points of the vehicle states w_ψ, w_θ and w_u (in the direction of the unit vector v_{veh_bf}). These set points can be determined by using the relationship of the sea current vector, the body and earth fixed velocity vector of the vehicle as well as the intersection point between a line and a sphere as shown in Fig. 6.

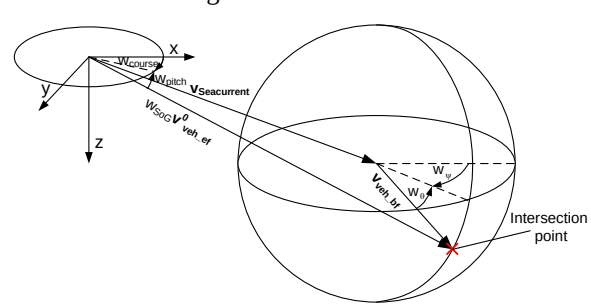

Fig. 6. Definitions of the velocities

IV. VEHICLE POSITION ESTIMATION

The vehicles use Kalman filtering (see [9]) to estimate the positions of their team mates as a base for the controller. Because every transmission of a position update between the vehicles causes a delay, an estimator implementation based on two Kalman filter with identical structures was preferred for realisation. The delay depends on the distance between the vehicles. While the Kalman Filter (KF) 1 performs the position estimation at all time, KF 2 is used for recalculation, whenever a new message is received from other vehicles containing position data. As the position data of the message is no longer valid (the other vehicle has moved since it sent the message), KF 2 uses the transmitted value to recalculate the values in the time between the sending and receiving of the message. At the end, the new value is transferred to KF 1. This is shown in Fig. 7 and will further be explained in this chapter.

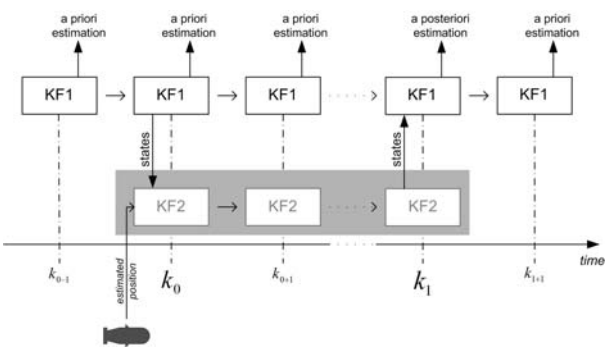

Fig. 7. Concept of Kalman realization

Within the Kalman filters, each vehicle is simulated by a simple kinematic state space model. The dynamics and the delay of the controllers are realized in an external model. The desired set values for the velocities to follow the predefined path are extracted from the mission plan. These values are the inputs for the combined model of vehicle and vehicle controllers. The two-dimensional state space model has the following structure:

$$\begin{Bmatrix} \underline{x}_k & = & \Phi \underline{x}_{k-1} + B\underline{u}_k \\ \underline{y}_k & = & C\underline{x}_k \end{Bmatrix} \tag{6}$$

with

$$\underline{x}^T = \begin{bmatrix} x & y & v_x & v_y \end{bmatrix} \tag{7}$$

x - position in x direction, y - position in y direction

v_x - velocity in x direction, v_y - velocity in y direction

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}; \quad B = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ K_{vx}dt & 0 \\ 0 & K_{vy}dt \end{bmatrix} \tag{8}$$

$$\Phi = \begin{bmatrix} 1 & 0 & dt & 0 \\ 0 & 1 & 0 & dt \\ 0 & 0 & 1-K_{vx}dt & 0 \\ 0 & 0 & 0 & 1-K_{vy}dt \end{bmatrix} \tag{9}$$

dt - step size of simulation

K_{vx} / K_{vy} - velocity transfer parameter.

We assume that in general a vehicle is not able to change its velocity from an old to a new value in an arbitrary short time step. This is expressed in (9). The new velocity is a combination of the old one and the new desired one. In this manner, the velocity transfer parameter is a vehicle specific time constant and adopts the vehicle's dynamics in regard to its velocity. This parameter has the unit (1/s) and was arbitrarily set to 1 in our simulation.

The observing vehicle uses the position kinematics of the observed vehicle to get position predictions. The KF 1 calculates only a priori values as long as no new value is transmitted from the observed vehicle. For instance, the algorithm for vehicle 2 estimating vehicle 1 at time step k is:

$$\begin{Bmatrix} \hat{\underline{x}}^{(-)}_{1,2;k} & = & \Phi \hat{\underline{x}}^{(-)}_{1,2;k-1} + B\hat{\underline{u}}_{1,2;k} \\ \hat{\underline{y}}^{(-)}_{1,2;k} & = & C\hat{\underline{x}}^{(-)}_{1,2;k} \end{Bmatrix} \tag{10}$$

At time step k_0, vehicle 1 transmits its current position value $\underline{y}_{1;k_0}$ in a data telegram to vehicle 2. At vehicle 2, the values $\hat{\underline{y}}^{(-)}_{1,2;k_0}$ are calculated at that moment. At time step k_1, the telegram arrives, when vehicle 2 currently calculates the values $\hat{\underline{y}}^{(-)}_{1,2;k_1}$. The position value from the telegram is stored as $\underline{y}^{(k_0)}_{1,2;k_1}$. Now, the a posteriori position values $\hat{\underline{y}}^{(+)}_{1,2;k_0}$ are calculated for the time step k_0 by KF 2:

$$\begin{Bmatrix} \hat{\underline{x}}^{(+)}_{1,2;k_0} & = & \hat{\underline{x}}^{(-)}_{1,2;k_0} + K_{k_0}\left[\underline{y}^{(k_0)}_{1,2;k_1} - C\hat{\underline{x}}^{(-)}_{1,2;k_0}\right] \\ \hat{\underline{y}}^{(+)}_{1,2;k_0} & = & C\hat{\underline{x}}^{(+)}_{1,2;k_0} \end{Bmatrix}, \tag{11}$$

where K_{k_0} is the Kalman gain. Then the values for the time interval k_0-k_1 will be recalculated. After this, vehicle 2 continuous to calculate the a priori values (KF 1) online until a new message from vehicle 1 arrives and the procedure starts again.

V. REALISATION AND RESULTS

As a base for demonstration, we chose a scenario where three marine vehicles are intended to perform a coordinated lawnmower maneuver in a triangle-shaped formation. We will use different strategies for the estimators to enable a control of the formation preservation as it was described. We assume that it takes ten seconds to execute the transmitting and receiving of a message between the vehicles, so each vehicle will send its position to the other vehicles every 30 seconds. We also assume that vehicle 1 in the middle of the formation has a disturbance in its velocity actuators and goes faster than ordered.

The simulator under MATLAB/Simulink is block-oriented. The block for a single vehicle is shown in Fig. 8. The Maneuver Processor executes the tasks of the Task Management, as shown in Fig. 4. The Controlled Vehicle

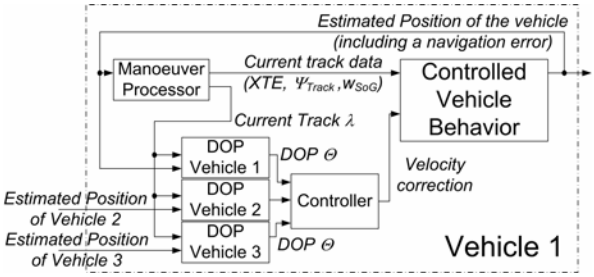

Fig. 8. Design of the vehicle models

Behavior executes the tasks of sea current compensation and State Control Loops (Fig. 4). In the lower part of the vehicle block there are the calculations of the Degree of Execution Θ and of the velocity controller, as explained in chapter 2. So every vehicle block needs the positions of the other two vehicles as input and provides the vehicle position (disturbed by selectable navigation errors) as exit.

The estimators we use have the same structure as the vehicle model. The only difference is that we replace the Controlled Vehicle Behavior Block with the linear kinematic State Space Model as described in chapter 4. So we separate the non-linear vehicle behavior into the non-linear Maneuver Processor and Controller (which are easy to simulate) and a linear vehicle model as a base for the Kalman filter. These estimators will also receive the communication messages with the position information of the other vehicles and use this to improve the estimation quality as described above.

To demonstrate our results, we will present different simulations. Case a) will skip the velocity controllers for the formation preservation and therefore does not need any estimators. This results in the worst case error for any scenario. Case b) will also be a theoretical case where the position results of all vehicles are directly used as input for the velocity controllers of the other vehicles without the employment of estimators. This will not work in reality; it may only show the theoretical best results. Within Case c), we use a structure shown in Fig. 9. Each vehicle employs two estimators, one for each other vehicle.

We show a fourth situation named case d) to take care of the following fact: The realization of an estimator for vehicle *m* from vehicle *n*'s view must consider that vehicle *m* will adapt its velocity according to its own estimation of the position of vehicle *n*. In case c), we disregards this fact and simply use the calculated position of vehicle *n* (here: vehicle 1) as input for the estimators of the other vehicles. A more realistic behavior needs to consider that the other vehicles do not know the exact position of vehicle *n*; they also use estimators and will therefore use faulty position values for vehicle *n*. Vehicle *n* needs to consider these errors to be more exact. Therefore, it employs estimators to calculate its own position, but from the view of the other vehicles. With other words, vehicle *n* 'estimates what the other vehicles estimate about vehicle *n*'. A similar construction for the evaluation of communication needs was originally proposed in [10].

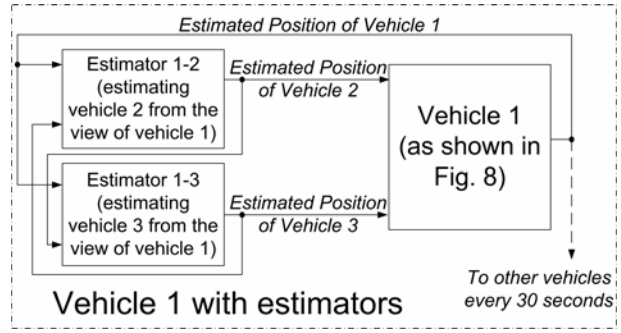

Fig. 9. Vehicle- and Estimator Structure for vehicle 1, case c)

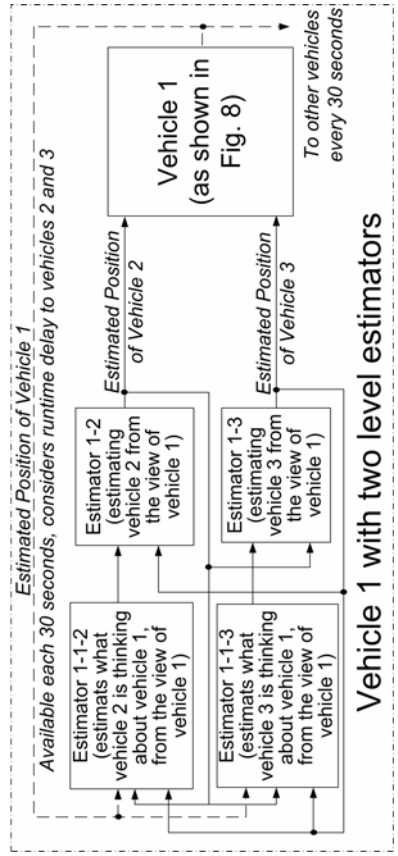

Fig. 10. Vehicle- and Estimator Structure for vehicle 1, case d)

As shown in Fig. 10, for case d) we employ two second-level estimators for each vehicle to estimate what the other vehicles think where the corresponding vehicle is at the moment. They get the information about the position from their own vehicle only every 30 seconds (just as well as the other vehicles via the acoustic communication link), to keep

TABLE I
SIMULATION RESULTS WITH POSITIVE VELOCITY ERROR OF VEHICLE 1

	Formation Deviation *FD*
a) Without any control	12.5996
b) With velocity control, without Kalman position estimator	0.4283
c) With velocity control and Kalman position estimator (not regarding velocity control)	0.4636
d) With velocity control and Kalman position estimator (regarding velocity control)	0.4594

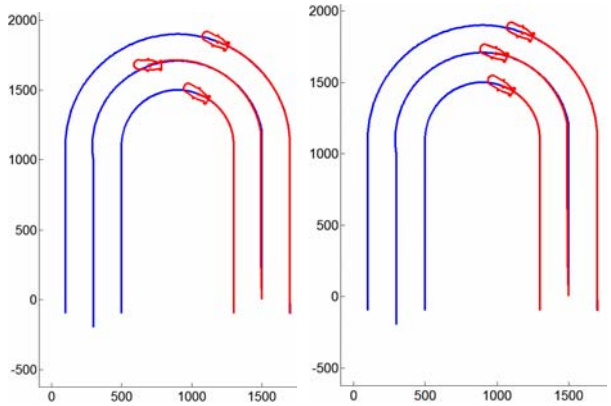

Fig. 11. Formation Deviation with velocity error on vehicle 1. Left: without formation control (case a); Right: with velocity control and Kalman position estimator (regarding velocity control) (case d).

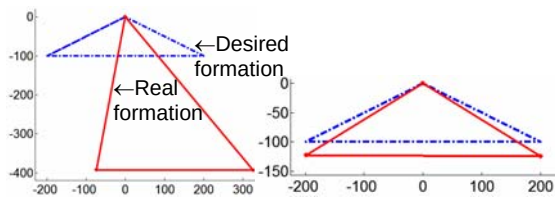

Fig. 12. Position of vehicle 2 and 3 relative to vehicle 1 at the same time step than in Fig. 11. Left: case a); Right: case d).

the situation realistic; this is why the corresponding arrow is dashed. This will make the simulation more complex; it will be interesting to evaluate whether this construction provides better results than case c). In Fig 11, 12 and Table 1, the results of the simulation are shown, where we set the weighting factor ξ_1, ξ_2 and ξ_3 (see chapter 2.B) to 1.

Table 1 shows that the introduction of the velocity controller results in a considerable improvement of the Formation Deviation (case a and case b). Assuming that the measured positions of all submarines are known to all other submarines, a Formation Deviation *FD* (see chapter 2) of 0.4283 can be reached (case b). This value is determined by the controller design (in case of this paper a P-controller). But, these position values are not known in real world applications. In case c, a Kalman based estimator is used for generating quasi-continuous positions values; the Formation Deviation *FD* of 0.4636 results. This value can further be improved by using the two- level estimators in case d, where a value for Formation Deviation *FD* of 0.4594 is reached.

VI. Conclusion

This paper has shown a new approach of team navigation for formation preservation of MUMVs in coordinated maneuvers. The adapted velocity controller needs the positions of all vehicles to keep the given formation. With a new metric, the Formation Deviation (3), different cases in gaining the vehicle positions were compared. Summarized, formation preservation without any controller cannot be reached. So, we recommend the use of the formation preservation controller. But this controller needs the vehicle positions of the whole group. At first we have shown the improvement in formation preservation using the vehicle positions assuming every vehicle knows all positions. But this case cannot be used in real world applications. There, no vehicle has all positions every time; the locations must be predicted. Therefore a Kalman filter concept was presented. This concept also considers the communication time delay between different vehicles. We compared two different cases employing Kalman Filters: In the first approach, each vehicle simply estimates the position of its mates. In the second approach, each vehicle also models the estimators of the other vehicles. As expected, the second approach produced better results, but the improvement was very small, so the higher complexity of the structure may not be reasonable in this case. In future research we will use these two approaches for other cooperated maneuvers to investigate whether a better improvement can be reached.

With these concepts the cooperated lawnmower for seabed observation can be processed with formation keeping.

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