A COOPERATION SCENARIO IN THE MARINE ENVIRONMENT: FIRST OUTLOOK

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Abstract: Marine environments offer suggestive scenarios for Automatic control and Cooperation strategies to be applied. The present paper focus on a particular one: Two ships towing together an off-shore oil retaining boom. Basic dynamical equations are presented for the combined displacement of both ships plus the boom. Computer simulation of basic manoeuvres works out the basic control implications of the problem and suggests cooperation among the ships as a more reliable technique to fulfil ships goals and minimize boom strain.

Keywords: Ship control, Manoeuvring, Cooperation.

1. INTRODUCTION

From ancient times, sailing has been a fascinating human activity. Ages of continuous effort have been required to evolve from the simple floating rafts to the actual complex vessels. As in many other human activities, experience has been the key to master the sea and science the way to explain and improve the achievements of experience.

But perhaps for being sailing a so ancient art, automation and control have been introduced mainly in recent times and only partially. The control effort still relies in human beings and this is especially true when marine manoeuvring is the topic.

Concerning feedback control applied to marine vessels, Fossen (2002) lists a wide number of examples of commercially available systems: Ship and underwater vehicle autopilots for course-keeping and turning control, way-point tracking trajectory and path control system for marine vessels, depth autopilots for underwater vehicles; torpedo control systems, attitude control system for underwater vehicles, dynamic positioning systems for marine vessels, positioning mooring systems for floating vessels, fin and rudder-roll stabilization systems, wave-induced vibration damping systems for high-speed craft, buoyancy control systems including trim and heel correction systems, propulsion control systems and forward speed control systems, propeller and thrusters control systems and energy and power management systems.

From the point of view of control problems; marine environments offer a wide source of suggestive scenarios:

- Seakeeping problems (Lloyd, 1998), has been the scope of recent efforts: To improve ship's stability and global performance by means of proper actuators such as fins, T-foils or flaps (De la Cruz, et al. 2004; Haywood, et al., 1995; Ryle, 1998). Such actuators require also some kind of control smartness to be operated properly.

- Manoeuvring is perhaps a still more varied field. It can include a single vessel or several ones in a wide range of scenarios:

The apparently simple operation of freight or person offshore transfer, involved a coordinated manoeuvre between two vessels. The degree of complexity depends on several factors; weather conditions, ships features, kind of freights to be transferred and human factors could be pointed out. Recent papers on related topics are (Kyrkjebo, 2003, 2004; Morishita, 2004).

The mutual manoeuvring between two or more sailing vessels to avoid a possible collision, taking into account the operational constraints and course objectives, compose also a complex system. In this context, towing cases are of new interest (Johansen, 2003).

Device deployment constitutes another interesting scenario of waterborne operation. The deployment of nets, set of buoys, barriers etc. which may be employed to mark or confine a particular sea area (for example, after an oil leakage). This scenario includes also the removal of wrecks and other recycling operations. Several watercrafts may cooperate to hold, transport and eventually deploy the device in a proper way.

Operational requirements in this case demand the capability of involved watercrafts to perform a proper dynamic positioning, the ability of them to deal with the device to be deployed in a well coordinated way and capability to react against possible modifications on the area to be bounded. The success demands the correct use and operation of the whole system as in the previously described operations.

The need of cooperative control in marine operations has been recognized recently by several authors and institutions. (Soentanto, et al., 2003; Stilwell and Bishop, 2000) are illustrative references. A way to deal with this kind of problems is to look at the more general robotics field, where cooperation between mobile agents is attracting research interest from years ago. Reference books of interest are (Weiss, 1999; Liu and Wu, 2001); recent relevant articles focusing on formations and agent interaction are (Tanner, et al., 2004; Billard, 2004).

The present paper contains the first steps towards a complete study of a deployment scenario; two boats cooperate to deploy a floating barrier. The study departs from a simplified version of ships and barrier dynamic equations.

2. PROBLEM APPROACH

For marine vessels moving in 6 degrees of freedom (DOF), 6 independent coordinates are necessary to determine position and orientation. The first three coordinates correspond to the position and the time derivatives to the speeds along the x, y and z axes. The last three coordinates and their time derivatives describe orientation and rotational speeds. The 6 different motion components are usually defined as, surge, sway, heave, roll, pitch and yaw.

Figure 1 shows the 6 degrees of freedom as they have been described.

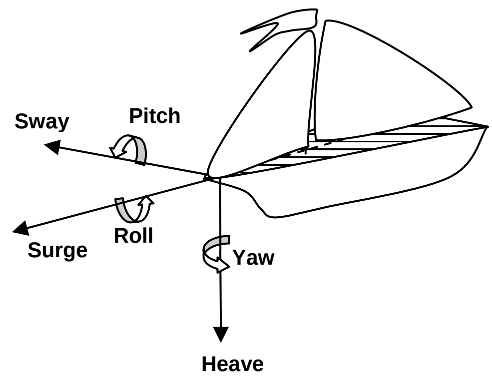

Fig. 1. Motion variables for marine vessels

In the present work, only surge, sway and yaw are taken into account for being more directly related with ship course description. Pitch, roll and heave, are more related with ship oscillation induced by waves motion. In the actual world, every six movements are coupled but in this first approach to the problem they will not be taken into account for simplicity reasons.

a) Simplified scenario

The scenario is made up by two identical ships which tow together a floating boom. This last, consists of a certain number of identical floating rigid elements. Two consecutive elements are jointed by a hinge, so that one can swing relative to the other. The whole set of elements form a sort of chain in which each rigid element acts as a link. Each one of the two tip links of the boom is jointed to the stern of one ship. Fig.2 shows a schematic view of the described scenario.

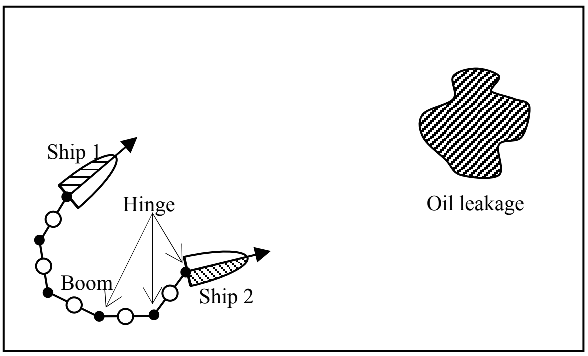

Fig 2. Schematic scenario view

For ships and boom links, only their lengths will be considered as relevant for dynamical analysis.

Ships are described by their mass, mass inertia moment and three drag coefficients that represent the resistance to motion through the fluid along surge, sway and yaw coordinates. Propulsion in surge direction is considered in terms of power and steer action is also represented in terms of power to generate a moment in the yaw direction. The combined effect of propulsion power and steer power determines the ship course; both variables will be the input variables to be operated for control purposes.

Booms links are defined also by their mass, mass inertia moment and drag coefficients similar to those employed in the ships. Strains in the ends of the links complete the description for the boom dynamic.

b) Mathematical approach

The motion of a ship, in the x-y plane, can be described with the following equations:

$$m_b a_{bx} = \left[F_m - \mu_l\left(v_{by}\sin(\theta) + v_{bx}\cos(\theta)\right)\right]\cos(\theta) - \mu_t l_s\left(v_{bx}\sin(\theta) - v_{by}\cos(\theta)\right)\sin(\theta) \quad (1)$$

$$m_b a_{by} = \left[F_m - \mu_l\left(v_{by}\sin(\theta) + v_{bx}\cos(\theta)\right)\right]\sin(\theta) - \mu_t l_s\left(-v_{bx}\sin(\theta) + v_{by}\cos(\theta)\right)\cos(\theta) \quad (2)$$

$$M - \mu_a l_s \omega_b = I_b \alpha_b \quad (3)$$

where m_b represents the mass of the ship, a_{bx} and a_{by} represent the acceleration in axes x and y, F_m is the surge force, M is yaw moment, μ_l., μ_t, μ_a are the drag coefficients in surge, sway and yaw, l_s is the length of the ship, I_b is the moment of inertia.

Figure 3 shows the geometry of the problem with the angle θ, the ship's speed v_b, and the position of the ship.

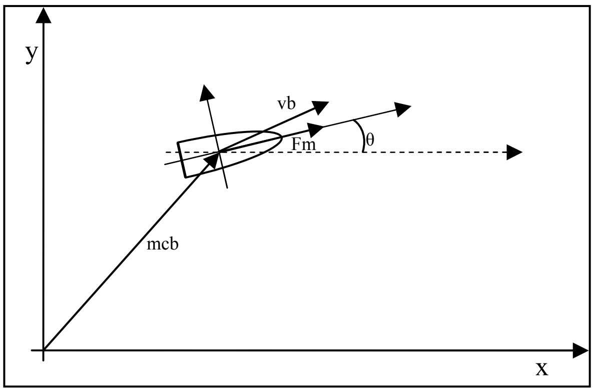

Fig. 3. Ship main variables

The motion of the boom, which is attached to the ships, is deduced by first considering a link and then combining several links (imposing the corresponding closing conditions).

Figure 4 shows the geometry of the boom, which is a chain of links.

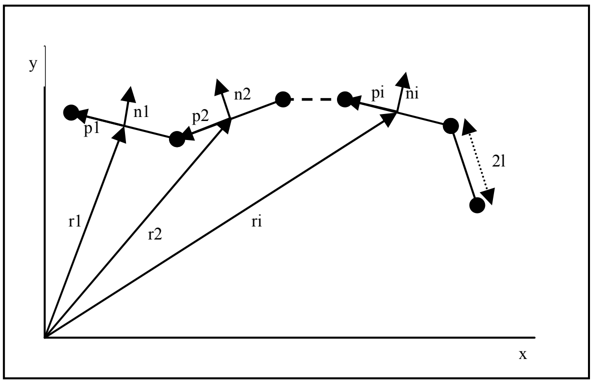

Fig. 4. Geometry of the boom

The motion of a single generic link is given by:

$$\vec{T}_{i,i+1} - \vec{T}_{i-1,i} - \frac{\left(\left|\vec{v}_i \cdot \vec{n}_i\right|s + \left|\vec{v}_i \cdot \left(-\vec{p}_i\right)\right|q\right)}{\left|\vec{v}_i\right|}\vec{v}_i = m\vec{a}_i \quad (4)$$

Were, T represents the strain in a tip of the link, n_i is a normal vector, p_i is a vector opposite to the sense of the link, q and s represent longitudinal and perpendicular drag coefficients and m is the mass of the link.

$$\left(\vec{T}_{i,i+1} \cdot \vec{n}_i\right)l + \left(\vec{T}_{i-1,i} \cdot \vec{n}_i\right)l - A\omega_i = I\alpha_i \quad (5)$$

Were l is half the length of the link, A is a drag coefficient, and I is the moment of inertia.

The closing condition is imposed by means of eq. (6)

$$\vec{r}_i - l\vec{p}_i - l\vec{p}_{i+1} - \vec{r}_{i+1} = 0 \quad (6)$$

Were r_i is the position of the link. This equation is included to assure boom continuity

The problem to be solved starts from an initial condition, with the boom attached to the ships (they can be considered as links too) and the ships starting to move. The system of equations is solved iteratively along small time intervals.

3. PRELIMINARY COMPUTER EXPERIMENTS

The research begins with the simplest case. Both ships try to go in parallel, along a straight path. Figure 5 shows the result for a boom composed of five elements, the arrows in the extremes represent the successive positions and orientation of both ships. The boom has been represented by lines with a dot in the centre of each element. The boom pulls the stern of the ships, and the ships rotate. Eventually, both ships make a tug of war. The need of a control action on the rudders, to counteract the boom tug, is clear.

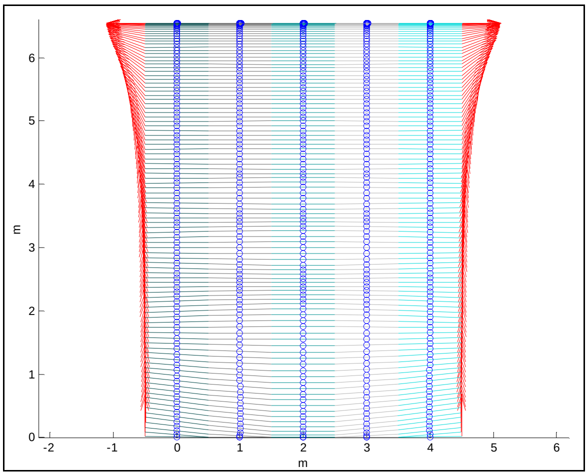

Fig.5. Motion of the system without control.

It is important to notice that initial conditions have been highly forced. So, ships start their movement forming a square angle with the boom, which has been arranged all its length extended. This means that slight movements of the ships are going to generate large strains in the boom.

These initial conditions are hardly expectable in the real world, but they have been considered because represent an extreme case in which the effects among ships and boom dynamics are highly interrelated.
Now, a simple proportional control is put into action, to force the ships to follow a straight course. Figure 6 shows the simulated experiment. In this case, the control algorithm applies a moment proportional to the course error to counteract the effect of the boom strain and maintain the ships courses

A transient appears at the beginning, due to the tightness of the boom and then the ships tend to join smoothly, bending up the boom.

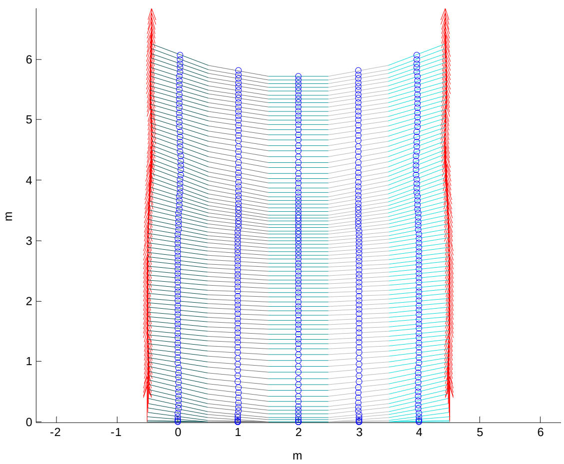

Fig. 6. Motion of the system with individual course control

It seems that the control of the ships course must consider the distance between them. A proportional control of the mutual distance has been added to the proportional course control in each ship. This new control action has been added to the previous one. Now, the total moment applied to each ship is the result of two components, one proportional to the course error plus other proportional to de difference between the actual distance between the ships and the desired distance between them. Figure 7 shows the good results obtained: both ships approach till they reach the set point distance. Obviously, the strain in the boom diminishes and the system yields a better performance. This can be considered as a coarse mode of coordination control.

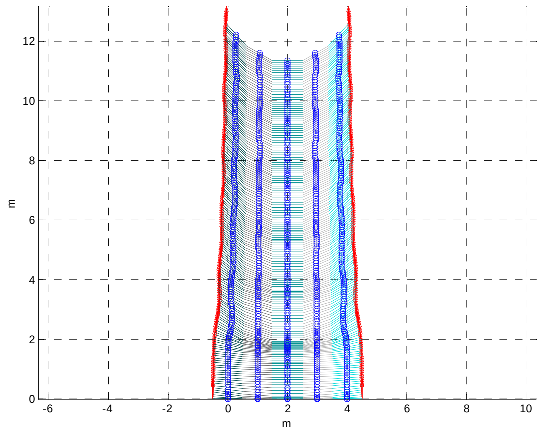

Fig. 7. Motion of the system with coordination control

Figure 8 compares the values of the horizontal component of the tension between the ship located in the left side and the last link of the boom at which the ship is connected, for the three previously described cases.

For the case on no course control, the tension increases at the same time that the ship rotates counter clockwise. Eventually, this tension will become equal to the force exerted by the ship in the surge direction.

In the case of course control, there are three different phases. First the course of the ships matches it set point. No control action is exerted but after a while ships begin to turn outwards, the control systems reacts and as a consequence the tension begin to rise The combined effect on the tension plus the yaw moment exerted to amend the course causes that the ships were dragged by the boom inwards. The Tension reaches a maximum at some instant between 10 and 15 seconds, after this time, it begins to decrease due to the progressive approach of both ships and the bending of the boom.

The last case, when course and distance between ships is controlled, shows a sharper maximum than the previous one, located between 5 and 10 seconds. The reason is that the yaw moment acts from the beginning; as far as ships try to fulfil the set point impose to their mutual distance. Nevertheless, the tension falls after 15 seconds remaining for the rest of the period showed below the value of the tension for the previous describe case.

It also valuable to notice that there is still a remaining ripple in the last two cases studied, due to the strain exerted by the boom and the control effort that try to counteract this.

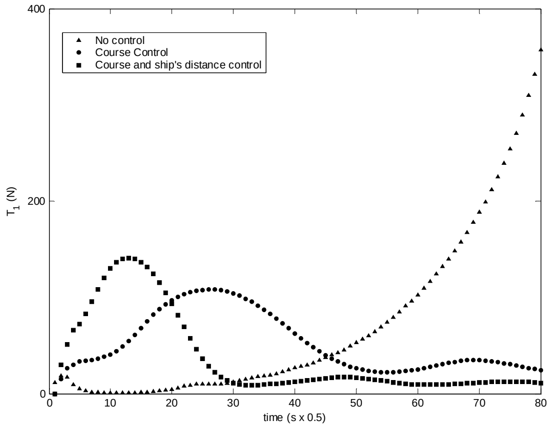

fig.8, Comparison among the strains reached between the left side ship and the first link of the boom for different cases: No course control is applied, individual course control is applied and course control and mutual distance between both ships is applied.

Strains applied to the boom should be taking into account also before perform whatever manoeuvre. In the present study no limit has been imposed to these but it is quite obvious that there is a maximum limit for the strain that the boom can bear. After this limit the boom breaks. So, those manoeuvres that exceed this limit should be avoided.

Figure 9 shows also another interesting effect. It represents the angle between the ship direction (from aft to bow) and the ship velocity direction for both ships and for the two last cases discussed previously. In the first case, only course control applied, the left side ship presents always a positive angle and the right side ship presents a symmetrical situation. This means that during the whole period showed both ships are dragged inwards by the boom strain. This effect tends to diminish with time, as the strain of the boom is more and more relaxed.

In the second case, both ships sail nearer and the angle described begins to oscillate around cero. In this case, the reason for the difference of orientation between the ships and their velocities is due to the inertia of the ships; these change their course but the velocity remains still the same for a while, following a little bit delayed the new course of the ships.

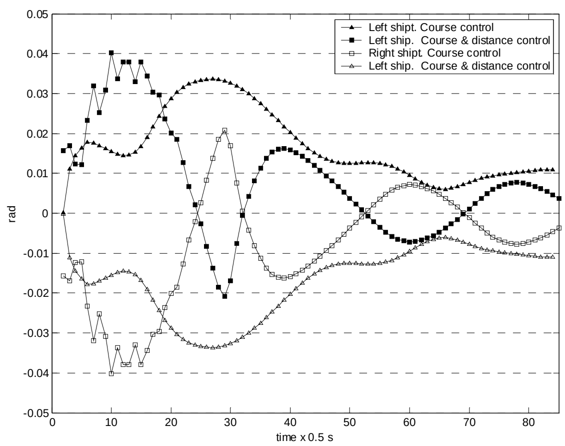

fig.9, Angle between ship direction and ship velocity direction

4. INITIAL MANOEUVRING AND CONTROL EXPERIMENTS

It is clear that for real cases, course changes must be studied. The simplest case is a single turn. Figure 10 shows a 45º right turn. As can be seen in the figure, the outer ship must cover a longer distance to keep up a synchronous turn, if both ships have the same speed the outer ship delays. When the new course is reached, the outer ship is delayed.

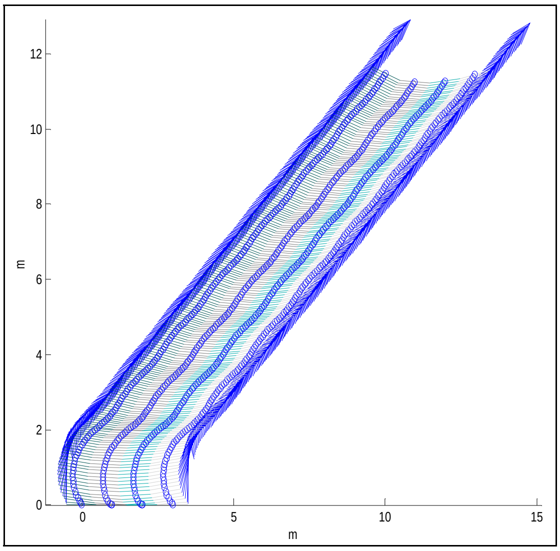

Fig. 10. System turn, ships with same speed.

Indeed the speed of the ship must be adjusted for a correct turn of the system. A speed control is added, with a correction of the speed in function of the angle between the desired course and the line which links both ships, which should be square. Fig. 11 shows the effect of this control action. Again, only a 'proportional to the error' control algorithm has been employed

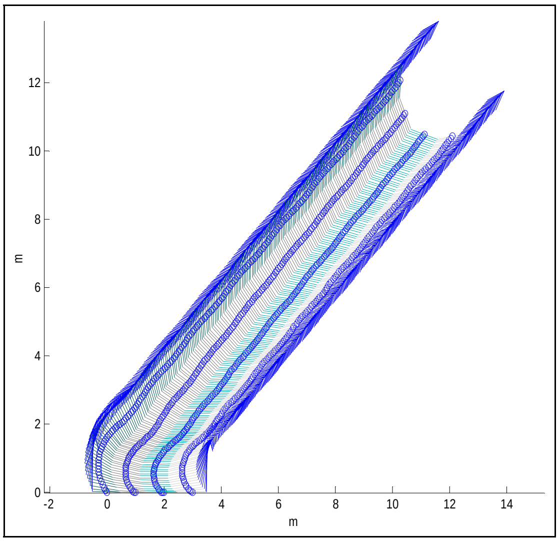

Fig. 11. System turn with alignment control

5. MORE COMPLEX MANOEUVRES

The final objective o a boom deployment should be the confinement of an oil leakage or other kind of harmful products. This last example considers the pursuit of a movable objective. The desired course for both ships is updated in any iteration according to the new position of the movable objective. Fig 12 Shows the results for the case of a hypothetical objective that follows an elliptical trajectory (crossed line in the figure).

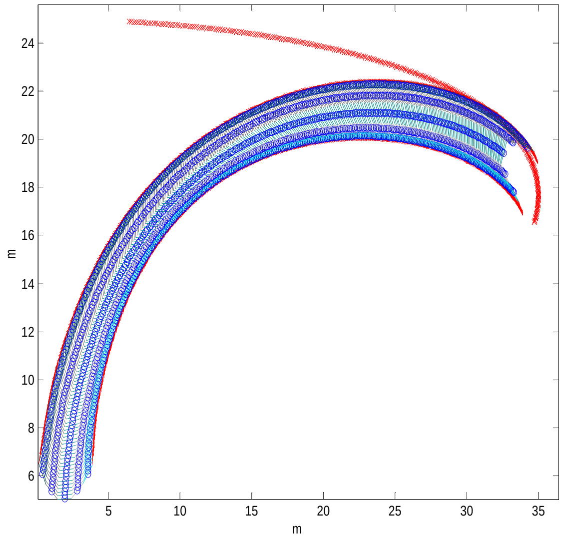

Fig. 12. Movable objective pursuit

For this particular case, every control actions described in previous paragraphs have been employed. Notice how the distance between ships varies along the turn. It seems that this behaviour should be improved by an adequate cooperation strategy on top of control.

6. CONCLUSIONS

The present paper is devoted to open a new topic in the context of cooperative marine robotics. It has been motivated by a recent spill-over in the Spanish coast. It was observed that the confinement of oil leakage by ships towing booms is a difficult coordination task. Actually, only the simplest team, formed by two ships and one boom, was put on task. It was intriguing to analyse why it is difficult. So a simple scenario, two ships towing a boom, was simulated in order to state a control coordination problem for further studies.

In this paper, the problem was stated in mathematical terms, and a sequence of cases, from the simplest one, was studied. The various needs of control (coordinated) interventions appeared, and, for the moment, were toughly solved. Indeed, a future research will focus on better control.

The scenario is clearly suggestive, not only from the control point of view, but also from the cooperative strategies perspective.

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