Journal of Maritime Research, Vol. VI. No. II, pp. 71-82, 2009

ISSN: 1697-4840

APPLICATION OF AN AERONAUTIC CONTROL FOR SHIP PATH FOLLOWING

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Received 25 September 2008; received in revised form 5 October 2008; accepted 30 May 2009

Abstract

Control design for marine autonomous vehicles is a subject of great interest in control systems. These vehicles are strongly non linear and show complex hydrodynamics effects that make the control design difficult. Besides, coordinated control deals with the control of several independent objects to reach a global goal. Therefore the CPF deals with the problem of controlling a group of unmanned vehicles along a given path, while they are keeping a desired formation. In a first approach to the problem of coordinated control of formations, the control of an underactuated autonomous vehicle, a ship, has been treated to reach and follow a given reference. For the control of the ship, it has been used a "Line of Sight" algorithm, initially developed for the control of an aircraft, applied to marine vehicles, allowing a smooth and accurate control and path following.

Keywords: nonlinear control, unmanned vehicles, path following, marine control.

INTRODUCTION

The problems of control of autonomous vehicles, that are dealt in a wide range (Aguiar 2003, 2007) (Fossen 2000), can be classified in three fundamental groups.

— Point stabilization: Its aim is to stabilize the vehicle in a fixed point in a particular orientation.

— Trajectory tracking: In this problem the vehicle must follow a trajectory parameterized with respect to the time.

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— Path following: In this problem the vehicle must converge on a particular path and follow it with a desired speed. The main difference with respect to the trajectory tracking is that there are no time references in path following.

The difficulty to solve each of these problems is strongly dependent on the vehicle configuration and it is of very interest when the vehicle is underactuated.

It is important to emphasize that the drift velocity in the underactuated marine vehicles is often linearly independent respect to the forces that actuate over them, so that it is not possible to convert the model into another model without drifting.

Furthermore, the fully actuated systems are expensive and, in many situations, it is not convenient to equip the ship with more actuators due to weight problems, complexity, efficiency and other considerations. For this reason, the control of underactuated vehicles is a very active investigation topic.

The path following systems are widely studied in (Encarnação 2001) (Ghabcheloo, 2007) (Pettersen, 2006) for example.

In this control problem the vehicle's forward velocity does not have to be controlled with high precision, so that an adequate orientation control to drive the vehicle along the desired path is enough. Nevertheless, the forward speed can be controlled to fulfill some soft time references.

Usually, this kind of control reaches a convergence with the path smoother than the trajectory tracking control, and moreover, the control signals obtained do not have too much tendency to saturation.

In this line, this work deals with the path following of an unmanned surface vessel (USV) to be used in cooperative tasks with other ships in formation control (Ihle, 2007) (Barisic, Vukic, Miskovic, 2005).

CONTROL LAW

Path planning problems are related to the design of control laws that force a vehicle to reach and follow a reference. The degree of difficulty to solve this problem depends on the vehicle's configuration.

The control logic consists in a simple algorithm that calculates the necessary rudder rate to reach the desired path in a smooth way.

An anticipatory control element is used for the control which overcomes the inherit limitation of feedback control to follow curved paths. This anticipatory control element and guidance logic is described deeply in (Park, Deyst & How, 2006) for its use in unmanned air vehicles (UAVs), where its stability is demonstrated. Here lies one of the new approaches of this work: the use of this aeronautic control for marine vehicles.

The basic idea is to do path following by using an imaginary point moving along the desired path as a pseudo target, as in the common LOS control algorithm. It can be considered as an element of anticipation for the upcoming desired path.

In the forthcoming approach, we consider two reference frames, one inertial frame in which the variables referred to it will be expressed without sub index, and a body fixed frame, which will move with the vehicle fixed at its mass centre. This second frame has its x-axis aligned with the vehicle's forward velocity vector (figure 1).

A line of sight (LOS) of 1000m is used to compute the error between the desired and the real path followed by the vehicle. In figure 1 the variables used to calculate the error between the desired and the real path are shown, so the distance 'd' between them can be controlled.

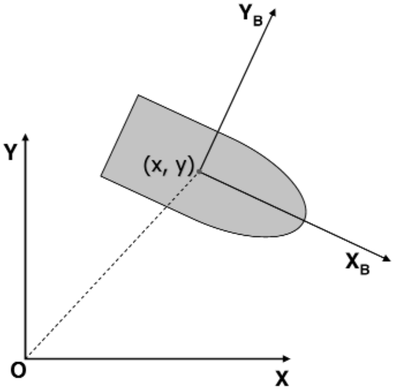

Figure 1: Reference frames.

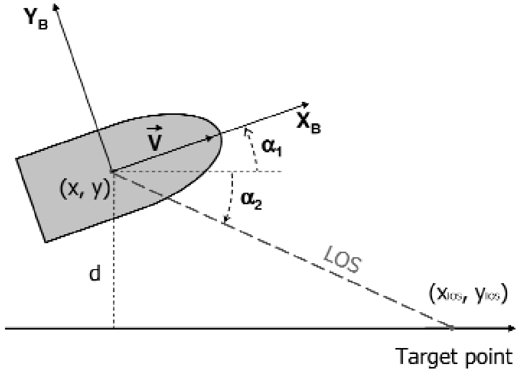

Figure 2: Control variables.

The algorithm consists firstly in finding the point in the desired trajectory that is at the distance of LOS. Then, the angles α_1 and α_2 are calculated, the first one as the inverse tangent of the ship's velocity coordinates, and the second one, as an inverse tangent as well, but in this case of the vector that joins the vessel to the point in the path at the distance of LOS.

$$\begin{aligned} \alpha_1 &= \arctan(v_y / v_x) \\ \alpha_2 &= -\arctan(y_{LOS} - y / x_{LOS} - x) \end{aligned} \tag{1}$$

The sum of these two angles is used to calculate the yaw rate, which will feed the control of the craft.

$$\begin{aligned} \alpha &= \alpha_1 + \alpha_2 \\ w &= -2 \cdot \frac{U}{L} \cdot \sin(\alpha) \end{aligned} \tag{2}$$

Where w is the yaw rate, U is the advance speed and L is the distance of LOS. The yaw rate is integrated to obtain the yaw angle as a control course input to obtain rudder angle for the ship.

From this equation we can observe two properties. The first one is that the direction of the acceleration depends on the sign of the angle between the line of sight segment and the vehicle velocity vector, so the vehicle will tend to align its velocity direction with the direction of the Line of Sight segment. The second one is that at each point a circular path can be defined by the position of the reference point, the vehicle position and that is tangential to the vehicle velocity vector. The acceleration command generated is equal to the centripetal acceleration required to follow this instantaneous circular segment.

Hence the guidance logic will produce a lateral acceleration that is appropriate to follow a circle of any radius R.

About the length Line Of Sight some considerations can be made:

— The direction of LOS makes a large angle with the desired path, when the vehicle is far away from the desired one.
— The direction of LOS makes a small angle when the vehicle is near to the desired path.

Therefore, if the vehicle is far from the desired path, then the control law rotates the craft so that its velocity direction approaches the desired path at a large angle. If the vehicle is close to the path, it is rotated so its velocity direction approaches the desired path tangentially (Park, Deyst & How, 2006).

SIMULATION EXAMPLES

Now we can see the control explained above in several simulations for different paths.

Straight lines

The first case that will be studied is when the ship must follow a path that converges to a straight line. Two cases will be considered: when the ship starts near or in the desired path, and when it does it in a distant position.

In this scenario, figure 3 shows when the ship starts the path following in the desired path, which converges to a straight line. The precision of the control law can be observed from this figure in the good performance made by it. It can be observed too how the ship converges to the desired path in an oscillating way at the beginning because it starts with an inadequate orientation of 45º instead of the 0º of the path.

Figure 4 shows when the ship starts in a distant position respect to the desired one. It can be seen how the ship reaches and follows the path as it is desired, achieving a simulated path of high accuracy.

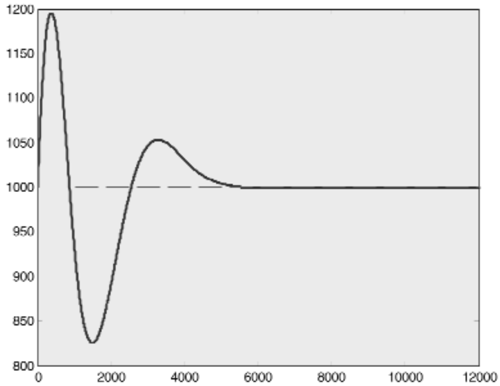

Figure 3: Desired (--) and followed path (-).

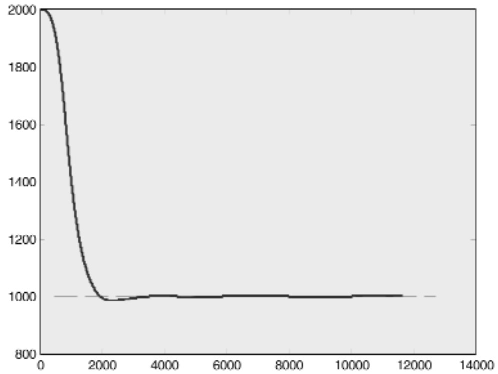

Figure 4: Desired (--) and followed path (-).

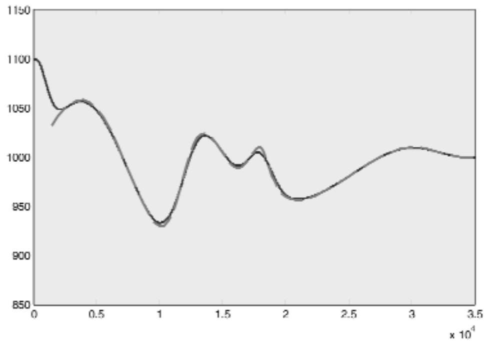

Figure 5: Desired (--) and followed path (-).

In this example, the ship searches the nearest point of the desired path and takes the adequate orientation to reach this point. Once this point has been reached, the 'line of sight' algorithm chooses the next point and so on along the path. As it can be seen from figure 4, the ship follows the desired path with a high precision once it has been reached, although in this case, despite of the ship starts far away from the desired position, it takes less time than before to reach accurately the desired path. It is because the ship can take a correct orientation while it is getting close to the desired path and it does not have to leave the path to converge to it adequately.

Perturbation from a straight line path

In this case, it is shown how the ship follows a path that is a perturbation from a straight line. The two possibilities commented above will be shown. First when the ship starts close to the desired path (figure 5).

The second case, when the ship starts far away from it, is shown in figure 6.

As it can be seen, the ship follows with great accuracy the desired path, but in this case it can be seen at the beginning how the path followed by the ship converges to the desired one a little bit rougher.

Circular path

As third scenario, it will be studied when a circle is defined as the desired

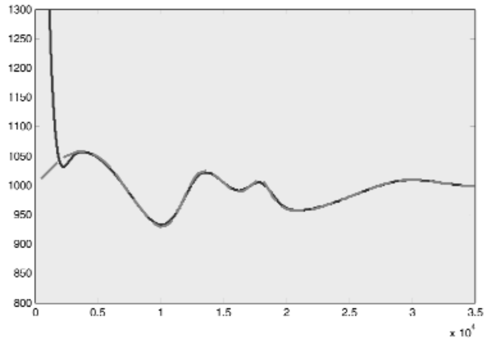

Figure 6: Desired (--) and followed path (-).

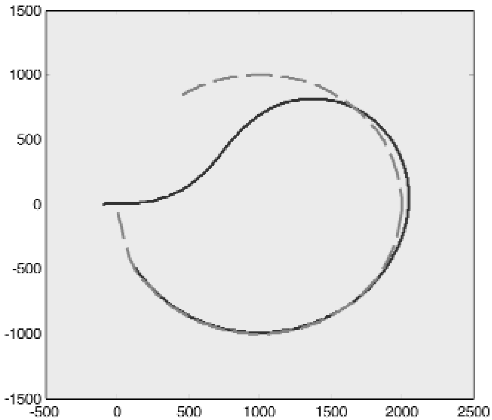

Figure 7: Desired (+) and followed path (-).

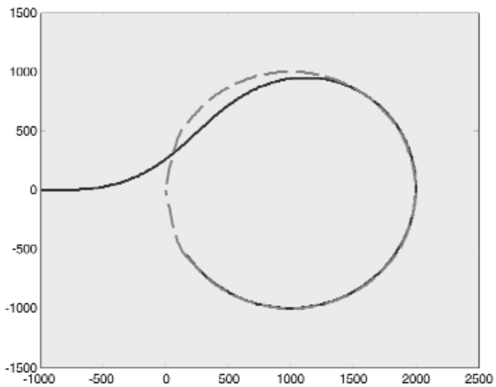

Figure 8: Desired (--) and followed path (-).

path. The two possibilities studied in the previous point will be considered too, when the ship starts near or in the desired path, and when it starts in a distant position.

First, when the ship starts in the desired path is shown in figure 7. It can be seen how, at the beginning, the vehicle does not follow the desired path because it has started with an inadequate orientation and must correct it. While the orientation is being corrected, the point to reach is changing to another nearer and easier to reach. Once the desired path has been reached, the vessel follows it with high accuracy as it can be seen at the end of the path.

Now, the case in which the ship starts in a distant point is shown in figure 8.

In this example it can be observed that the path is followed with higher accuracy at the beginning due to that the ship starts in a distant position and can reach the desired path in a smoother way.

It can be seen from the previous examples how the ship converges to the desired path as soon as it can, following the path with high accuracy once this path has been reached. It gives a simple control law with a very good fit in path following. In the next example it is shown how this control works very well not only in straight and circle paths, but also in a random path with sudden and smooth changes.

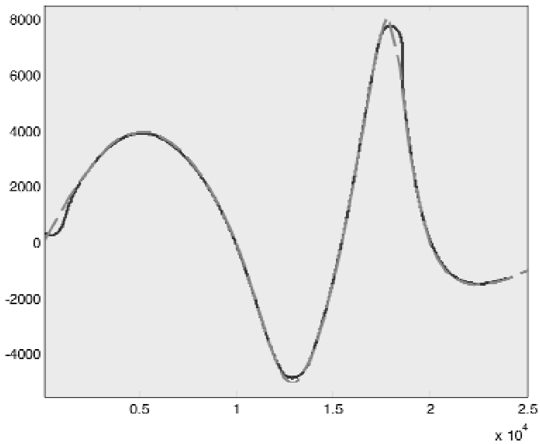

Figure 9: Desired path (--) and followed path (-).

Arbitrary path

In this case the advance speed is again maintained as a constant control input. In figure 9 it can be seen how the ship (blue line) follows the path (- red line) with high accuracy for a desired arbitrary way with sudden changes, and with a starting point out of this desired path.

In this case it can be seen how the control law fits very well the path to follow, achieving a very good control law for USV.

CONCLUSIONS

In this work a control law for aircrafts applied to Unmanned Surface Vessels (USV) has been presented. This control law shows a simple way to control USV for path following. In the different simulation examples a great fit in several situations has been demonstrated, showing that this kind of control can be used for formation control so the ship follows very well its desired path.

Besides this simple control law allows its experimental application that will be tested in future works, within the commented formation control.

ACKNOWLEDGMENTS

The authors wish to thank the Spanish Ministry of Education and Science for its support under PLACOMAR project, DPI2006-15661-C02.

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SEGUIMIENTO DE UN CAMINO POR UN VEHÍCULO AUTÓNOMO

RESUMEN

El diseño de controladores para vehículos autónomos marinos es un tema de gran interés dentro de los sistemas de control. Esto es debido a que estos vehículos son fuertemente no lineales y exhiben complejos efectos hidrodinámicos que dificultan considerablemente el diseño de control.

Los problemas de control de movimiento de vehículos autónomos, que se tratan ampliamente en la literatura (Aguiar 2003, Fossen 2002), se pueden clasificar en tres grandes grupos fundamentales:

— Estabilización en un punto (point stabilization): Este problema es también conocido como posicionamiento dinámico, el objetivo es estabilizar el vehículo en un punto fijo y en una determinada orientación.
— Seguimiento de trayectoria (tracking): En este problema el vehículo debe seguir una trayectoria que se encuentra parametrizada en el tiempo.
— Seguimiento de camino (Path following): En este problema el vehículo debe converger hacia un camino preestablecido y después seguirlo con una velocidad de crucero. La diferencia fundamental con el seguimiento de trayectoria es que en el seguimiento de camino no hay referencias temporales.

Este trabajo se centra en este punto, en el seguimiento de un camino por parte de un vehículo autónomo, para aplicarlo en trabajos futuros a un conjunto de vehículos moviéndose en formación.

De este modo, en una primera aproximación al control coordinado de formaciones, se ha tratado el control de un vehículo autónomo subactuado, un barco, para alcanzar y seguir una determinada referencia, para aplicarlo posteriormente al control de varios barcos que actúen de forma coordinada siguiendo cada uno su propio camino previamente especificado.

Para el control del barco se ha usado un elemento de control anticipatorio el cual supera la limitación del control por realimentación para seguir caminos curvados. Este elemento anticipatorio y la lógica de orientación están basados en el control desarrollado por Park, Deyst & How (2006) para su uso en vehículos aéreos autónomos. En este aspecto reside uno de los nuevos enfoques de este trabajo, el uso de un control aerospacial en vehículos marinos.

La idea principal de este control es hacer el seguimiento de la trayectoria usando un punto imaginario que se mueve a lo largo del camino deseado como un pseudo

objetivo. Éste puede ser considerado como el elemento anticipatorio comentado para el camino deseado.

De esta manera, usando este control para el seguimiento de camino de los vehículos y una estrategia de coordinación y mantenimiento de formaciones es posible conseguir un movimiento coordinado de un grupo de vehículos.

MÉTODOS

Se usará el control aeronáutico explicado en Park S., Deyst J. and How J. P. (2006) para el seguimiento de camino por parte de un barco. La línea de horizonte (LOS) usada por el control para calcular el error entre el camino seguido por el barco y la trayectoria deseada será de 1000m. En la figura 10 se muestran las variables usadas para calcular el error entre los caminos deseado y real, y de este modo controlar la distancia 'd' entre ambos a través del control del timón.

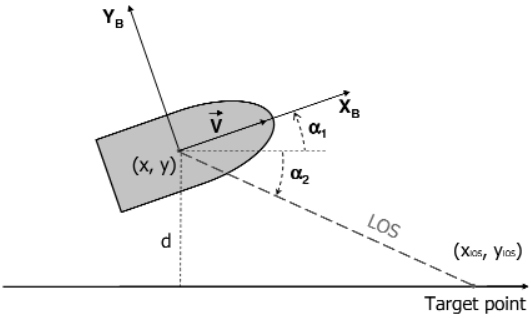

Figura 10: Variables para el cálculo del error de seguimiento de camino.

El algoritmo comienza buscando el punto en el camino deseado que se encuentra a la distancia de LOS. Tras esto, son calculados los ángulos α_1 y α_2, el primero como el arcotangente de las coordenadas de velocidad del barco, y el segundo de nuevo como un arcotangente, pero en este caso del vector que une el centro de masas del barco con el punto en el camino de referencia a la distancia de LOS.

$$\alpha_1 = \arctan(v_y / v_x)$$
$$\alpha_2 = -\arctan(y_{LOS} - y / x_{LOS} - x) \qquad (1)$$

La suma de estos dos ángulos es usada para calcular la variación del timón, que alimentará el control del vehículo.

$$\alpha = \alpha_1 + \alpha_2$$
$$w = -2 \cdot \frac{U}{L} \cdot \sin(\alpha) \qquad (2)$$

Donde 'w' es la variación de orientación del barco respecto al tiempo (velocidad angular), 'U' es la velocidad de avance y 'L' es la distancia de LOS. La velocidad angular de guiñada es integrada para obtener el ángulo de orientación como entrada del control de rumbo para obtener el ángulo de timón del barco.

En este caso la velocidad de avance se mantiene constante. En la figura 11 se muestra el resultado del seguimiento de camino de un barco usando el control explicado para un camino arbitrario deseado.

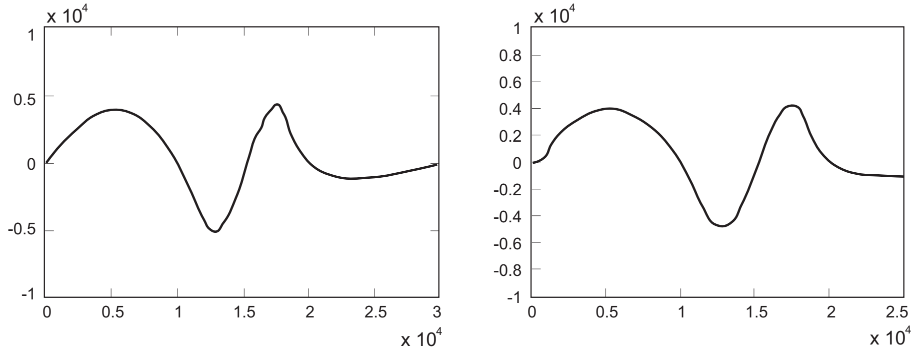

Figura 11: Camino deseado y camino seguido por el barco.

Se puede observar como el barco sigue de forma bastante fiel el camino deseado usando el control comentado.

CONCLUSIONES

Como conclusión al trabajo realizado, indicar que se ha utilizado un sistema de control aeronáutico adaptado a vehículos marinos, cuya lógica de funcionamiento se basa en dar una referencia de timón al vehículo en cuestión mediante un sencillo algoritmo que asegura la estabilidad del vehículo tanto en caminos rectos como circulares, proporcionando una convergencia exponencial al camino deseado.

Como se ha podido ver en los ejemplos mostrados, los vehículos, siempre que el camino definido esté dentro de lo permitido por su dinámica interna, siguen de forma fiel dicho camino deseado.

De la misma forma, este buen seguimiento de camino permite la creación de formaciones de vehículos moviéndose de forma coordinada, dejando este punto para futuros trabajos y desarrollos.