Available online at www.sciencedirect.com

ScienceDirect

IFAC-PapersOnLine 49-23 (2016) 199–206

Vision Restricted Path Planning and Control for Underactuated Vehicles

Albert Sans-Muntadas, Kristin Y. Pettersen and Edmund Brekke

Centre for Autonomous Marine Operations and Systems (AMOS)
Department of Engineering Cybernetics at NTNU, NO-7491
Trondheim, Norway. E-mail: [albert.sans, kristin.y.pettersen,
edmund.brekke]@itk.ntnu.no

Abstract: Autonomous vehicles can obtain navigation information by observing a source with a camera or an acoustic system mounted on the frame of the vehicle. This information properly fused provides navigation information that can overcome the lack of other sources of positioning. However, these systems often have a limited angular field-of-view (FOV). Due to this restriction, motion along some paths will make it impossible to obtain the necessary navigation information as the source is no longer in the vehicle's FOV. This paper proposes both a path planning approach and a guidance control law that allows the vehicle to preserve a certain object or feature inside the FOV while at the same time converging to the proposed path.

Keywords: FOV Constraint, Landmark Navigation, Path Planning, Guidance, Underactuated Vehicle

1. INTRODUCTION

One of the challenges that autonomous vehicles face is navigating in environments where information from the global positioning system (GPS) is not available. This is a challenge that affects vehicles and systems that operate indoors, inside mines, or underwater. An alternative to the GPS is often computer vision or acoustic systems.

Although computer vision and acoustic systems have proven to be able to produce accurate information, they sometimes rely on a single source of information, either because camera information tracks only a single visual landmark, or because there is only a single node available of an acoustic network. In such cases the ability to navigate depends on the constant observation of the source.

Unfortunately the sensors receiving these signals are often limited by the FOV, an angular restriction to observe the target. In some configurations the sensors have the ability to change their direction and therefore partially overcome this limitation (Stolle and Rysdyk (2003); Rysdyk (2006)). Other setups may instead have these sensors fixedly attached to the vehicle's frame and then the observability of the target becomes dependent on the vehicle's trajectory. This restriction make some paths blinded because by following them the vehicle loses vision of the target. (See Fig.1) In some setups this can compromise the navigation capabilities of the vehicle. The path planning problem thus becomes more challenging, as it should not only find a feasible collision-free path to connect the start and end points but also preserve the view of the target. This restriction is often referred as the field-of-view constraint. In Boyadzhiev (1999); Tucker (2000) it is observed that certain animals moving with respect to prey or a light source, follow a logarithmic spiral. This kind of spiral enables them to maintain the prey or light source in their field-of-view at all time during their motion. The existence of such trajectories in nature have inspired solutions to the FOV constraint. A formal definition of FOV is defined in Bhattacharya et al. (2007), where following a similar approach as the Reeds-Sheep car (Reeds and Shepp (1990)) describes a combination of straight lines and vision saturated curves that connect any two points in the plane. Later the optimal combination of trajectories is found and proven by Salaris et al. (2010). This work is further extended by Salaris et al. (2012) for side facing sensors.

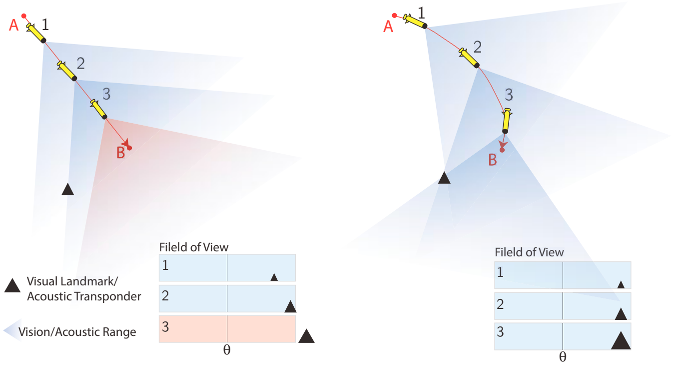

Fig. 1. Illustrative example of how two different paths can affect the observability of a target (▲) based on the FOV.

Maniatopoulos et al. (2013) proposes a control law that guides the vehicle towards a desired point by using model predictive control (MPC). In López-Nicolás et al. (2010); Salaris et al. (2011) different control schemes are proposed to follow the optimal path with an underactuated robot that can turn on the spot.

⋆ This work was partly supported by the Research Council of Norway through the Centers of Excellence funding scheme, project No. 223254 AMOS, and project No. 205622.

10.1016/j.ifacol.2016.10.343

A common approach for path following control of underactuated vehicles is also the line-of-sight (LOS) guidance (Fossen (2011); Healey and Lienard (1993); Breivik et al. (2008)). The LOS guidance approach has the advantage of being simple and has a very small computational load (Fossen et al. (2015)). This guidance law was also generalized for curved paths in Børhaug and Pettersen (2006) using a Serret-Frenet frame and extended to handle currents in Moe et al. (2014). However, the different versions of LOS guidance and its variants do not deal with restrictions in the FOV.

The path planning and path following problems with the FOV constraint are tackled in two steps in this paper. The first step is the design of a path by using logarithmic spiral paths, which are a particular type of trajectories that appear as general solutions in FOV problems being discussed in López-Nicolás et al. (2010); Salaris et al. (2012); Bhattacharya et al. (2007); Salaris et al. (2010). The second step is a guidance and path following control law for underactuated vehicles which is an extension of LOS guidance laws. This control law is specifically designed to follow the logarithmic spirals generated in the first step, and in addition it ensures that the vehicle's maneuvers preserve the view of the target. Compared to Salaris et al. (2011) the proposed solution trades some optimality in path length for the sake of robustness. Furthermore, since underactuated vehicles are considered as opposed to mobile robots, the vehicles are only allowed to move in the forward direction, avoiding zero velocity which would make the vehicle uncontrollable. By using Lyapunov theory we prove that the proposed guidance control law makes the vehicles converge to the path. In particular, we prove that the closed-loop error dynamics are globally asymptotically stable.

The paper is organized as follows: In Section II we propose a logarithmic spiral that connects two points with a path along which the landmark/transponder is kept within the vehicle's FOV. In Section III, we discuss the Serret-Frenet frame, a relative frame that moves along this path, and which is used in order to describe the guidance control law and examine the stability properties. Section VI formalizes the control objectives and describes the proposed guidance and control system. Section VII examines the stability properties of the closed-loop system and Section VIII simulates the behavior of the system for two cases: a ground vehicle and an underwater vehicle.

2. VISION PRESERVING PATH

The first objective of this section is to describe the reachable set of points $\Gamma \in \mathbb{R}^2$ that can be connected with at least one path, for an underactuated vehicle that moves only with forward velocity, and the motion restricted by a FOV.

The start point of this path is denoted $\boldsymbol{p}_k$, and the path should satisfy the condition that during the whole path a certain target: (▲) (landmark/transponder) must be preserved inside the FOV. When the set of reachable points Γ is defined, the next goal is to mathematically describe a vision preserving path that connects the starting point point $\boldsymbol{p}_k$ to another point $\boldsymbol{p}_{k+1} \in \Gamma$.

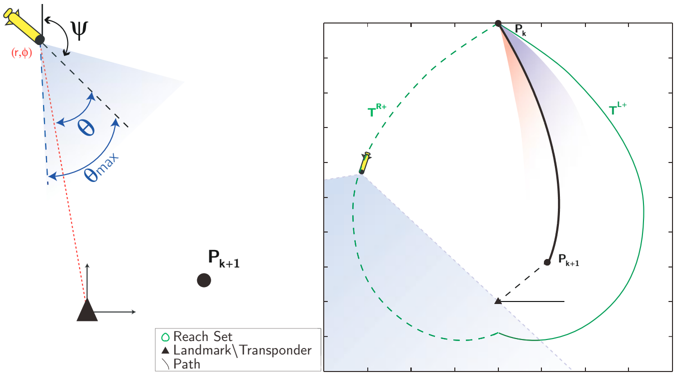

Fig. 2. On the left a representation of the FOV restriction: the angle θ the between the vehicle centerline and the target (▲) should be kept within the FOV boundary $\theta_{\max}$. The right figure shows the limit trajectories T^{R+}, T^{L+} along which the target (▲) is always at the FOV limit. The region inside the boundaries T^{R+}, T^{L+} contains the reachable set, and the black path is the proposed logarithmic-spiral trajectory.

The field-of-view is a solid angle in which a sensor can operate. Cameras and acoustic sensor tend to have this type of limitation. In this paper we assume that the origin of the earth-fixed coordinate system is defined at the landmark/transponder position. The objective is that the landmark/transponder is kept inside the FOV of the vehicle's sensor and can thus be expressed as follows:

Condition 1. $|\theta| \leqslant |\theta_{\max}| < \pi/2$

where θ is the bearing angle (See Fig. 2, left) between the vehicle centerline and the visual landmark/acoustic receiver.

For both objectives we assume:

Assumption 1. The FOV is forward looking, symmetric with maximum bearing $|\theta_{\max}| < \pi/2$ and aligned with the vehicle's centerline.

Assumption 2. The vehicle moves only with a forward speed U where, $u_{\min} \leqslant u \leqslant u_{\max}$ and the sway speed v is bounded by $|v| \leqslant v_{\max} < u_{\min}$.

This last is a necessary assumption for the path planning and control of underactuated vehicles, as they lose controllability when the velocity approaches zero.

2.1 Reach Set

In Salaris et al. (2010) the limit trajectories are described for a forward moving non-holonomic vehicle when the motion is restricted by the FOV. Such trajectories are logarithmic spirals and are also referred as: T^{R+} and T^{L+} (See Fig. 2 on the next page). These two trajectories represent the boundaries of the space that can be reached by a vehicle that only moves forward without violating the FOV restriction. These boundaries can also be expressed in a compact form as:

$$\Gamma_{P_p,\theta_{\max}} = \left\{(r,\phi+\phi_p) | r = r_p e^{-\frac{|\phi|}{\tan(|\theta_{\max}|)}}, \phi \in [-\pi,\pi]\right\} \tag{1}$$

To reach any point at the boundary under the FOV restriction stated in Equation 1, the only possible trajectory is by