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REAL-TIME SAIL AND HEADING OPTIMIZATION FOR A SURFACE SAILING VESSEL BY EXTREMUM SEEKING CONTROL

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ABSTRACT

In this paper we develop a simplified mathematical model representing the main elements of the behaviour of sailing vessels as a basis for simulation and controller design. For adaptive real-time optimization of the sail and heading angle we then apply extremum seeking control (which is a gradient based control law that drives the output of a linear or nonlinear system to its extremum) as an approach to maximize the longitudinal velocity. The basic idea behind extremum seeking and "how it works" is presented, as well as a simulation study on noise, convergence and stability issues.

Index Terms— autonomous sailing, nonlinear control, adaptive real-time optimization

1. INTRODUCTION

Autonomous sailing vehicles like sailboat- or the so-called landyacht-robots are relatively new amongst other fully automated vehicles such as autonomous aerial, marine, submarine or road vehicles. However, in comparison sailing vehicles have clean technological and energy-saving potentials due to their free and non polluting means of propulsion – the wind, also representing a real challenge in automation and control. Despite these facts, surprisingly very little attention was given to designing control algorithms for these kind of vehicles. Only a few papers deal with autopilots for sailing ships. Most of these studies such as [1],[2] and [3] propose control strategies based on techniques used in the field of Artificial Intelligence. These methods do not make use of the system dynamics itself thus preventing further theoretical analysis (e.g. to assess stability or performance) and scientific explanations of the principles of autonomous sailing. To the best of our knowledge no literature exists on real-time optimization by a computer for surge of a surface sailing vessel.

In sailing, a concern of most sailors is to optimize the longitudinal velocity or surge along a specific heading by trimming the sail in the best possible way. Since the dynamic response of sailing vessels will vary highly according to different types of sails and vessels as well as time varying environmental factors we suggest a non-model-, feedback-based real-time optimization method, the so-called extremum seeking approach (see [4] and references therein) – non-model-based also because thorough modelling of yachts or landyachts is very expensive and time consuming as it requires wind tunnel measurements. Thus the idea is to design a generalized, optimal controller which could be used for a wide variety of sailing vehicles and which can cope with a minimum knowledge of system dynamics driving the output of the system to its extremum.

Extremum seeking is an adaptive gradient-based control law that drives the output of a linear or nonlinear system to its extremum. It has proven to be an effective technology in a number of areas including formation flight control [5], chemical reactor control, PID parameter optimization [6], control of an autonomous vehicle without position sensing [7] and much more. Furthermore it is appropriate, both from a theoretical point-of-view, with its rigorous proofs, and a practical one, from its computational efficiency.

In this paper, we propose to model and study control aspects related to longitudinal velocity maximization of a landyacht through either sail control or both sail and heading control. A landyacht basically consists of a cart with three wheels and a sail. It is controlled by changing the front wheel angle and the sail angle for propulsion.

After this introduction, section 2 will be dedicated to formalize a simple model of a landyacht taking the basic kinematic structure as well as the basic dynamics of the system into account. Incidentally, other types of surface sailing vessels share similar characteristics. The objective of the following section is to introduce the reader to the basics of extremum seeking. Moreover it is dedicated to our first application proposed – velocity maximization via control of the sail angle for a specified, fixed heading. The third section focuses on a multiparameter extremum search where both the sail angle and the heading angle are controlled in order to find the direction promising the best speed performance. Simulation results are presented to illustrate the behaviour of the proposed schemes. Finally, a few concluding remarks end the paper.

2. MODELLING OF A LANDYACHT

In order to study control design issues for our sailing vehicle we would like to have at our disposal a model that is as simple as possible to gain insights on the problem at hand. Hence, instead of deriving a full model of a landyacht we concentrate on the basic kinematic structures as well as the essential dynamics responsible for the systems propulsion. To this end, first consider that our landyacht is nothing but, roughly speaking, a car whose propulsive part is a sail.

A well-known kinematic car model on the subject in mobile robotics and path planning (see for example [8]) is the so-called simple car which is also often referred to as bicycle model or Dubins car, represented in Figure 1. The vehicle is steered by the front wheel while the rear wheel center is an approximation of the motion induced by the two rear wheels of the cart. The kinematic model of the Dubins car which captures the movement of the landyachts cart can be expressed by the following set of differential equations.

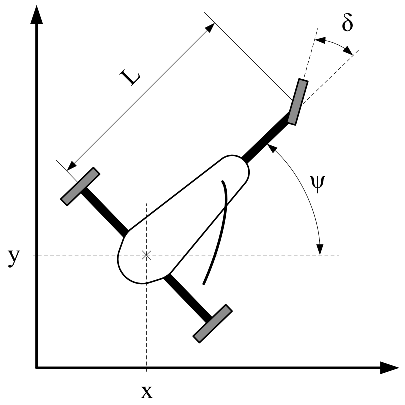

Fig. 1. The Dubins car model

$$\dot{x}(t) = v_u(t)\cos(\psi(t)) \tag{1}$$

$$\dot{y}(t) = v_u(t)\sin(\psi(t)) \tag{2}$$

$$\dot{\psi}(t) = \frac{v_u(t)}{L}\tan(\delta(t)) \tag{3}$$

where the coordinates x, y represent the position of the rear wheel center in the earth-fixed coordinate system and ψ is the landyachts heading angle. δ denotes the steering angle which is assumed to be limited within the interval $[-\delta_{max}, \delta_{max}]$, where $0 < \delta_{max} < \pi/2$. Parameter L indicates the distance between the front and the rear wheel axes (see Figure 1). Furthermore v_u denotes the longitudinal velocity or surge along the heading ψ.

However, since our vehicle is driven by the wind through a sail, its reachable velocities $v_u(t)$ are mostly dependent on the vehicles orientation ψ with respect to the wind, its velocity itself and the way the propulsion system, i.e. the sail, is trimmed. The maximum velocity v_{max} the vehicle can attain for a set of headings $\psi \in [-\pi, \pi]$, is intimately related to the so-called polar-performance-diagrams [9] (see Figure 4) well-known to sailors. From Figure 4 assuming the wind is comming from the north one can easily see that a sailing vehicle is able to go upwind with a certain angle with respect to the wind. If it is too close to facing the wind, it will loose propulsion or worse get stuck in the “no-go zone”. Despite this limitation a sailing vehicle is able to reach a destination upwind by performing zigzag-like maneuvers (called “tacks”) in the direction of the wind. That means that in a tack the no-go zone has to be crossed for a short period of time. The ability of the vehicle to perform a tack indicates the presence of some inertia effect on the velocity $v_u(t)$ being a fundamental behaviour in sailing. Thus, to model this behaviour, we propose the following equation.

$$m\dot{v}_u(t) + dv_u(t) = F_u(v_u(t), \gamma(t), \psi(t)), \tag{4}$$

where m denotes the mass of the vehicle, while d is a linear damping term in surge. The quantity F_u represents the longitudinal aerodynamic force or trust force propelling our vehicle, while being generated from interaction between wind and sail. As F_u is the force acting on the sail, it will depend on the way the sail is trimmed, represented by the sail angle γ and indeed it will vary highly according to different types and shapes of sails respectively (so will the shape of the polar-performance-diagram). In order to keep the model of the force simple we assume the ideal case, meaning that the wind blowing over the sail generates a force $\mathbf{F_{s_\perp}}$ that is perpendicular to the sail and proportional to the wind velocity vector. The decomposition of $\mathbf{F_{s_\perp}}$ yields the driving force with its absolute value F_u. In the following, we derive F_u from Figure 2 illustrating the development of the aerodynamic force $\mathbf{F_{s_\perp}}$.

Two coordinate systems are used. The earth-fixed (x, y), and the body-fixed (u, v) coordinate system. Let us first examine the velocity triangle depicted. It is a vector sum of the true wind velocity $\mathbf{v_{tw}}$ (relative to ground) and the longitudinal velocity $\mathbf{v_u}$ of the landyacht resulting in an apparent wind $\mathbf{v_{aw}}$ which is the wind experienced by the vehicle. Hence,

$$\mathbf{v_{aw}} = \mathbf{v_{tw}} - \mathbf{v_u}, \tag{5}$$

where the angle between the x axis and the true wind is the true wind angle α_{tw}, while the angle between the longitudinal u axis of the vehicle and the apparent wind

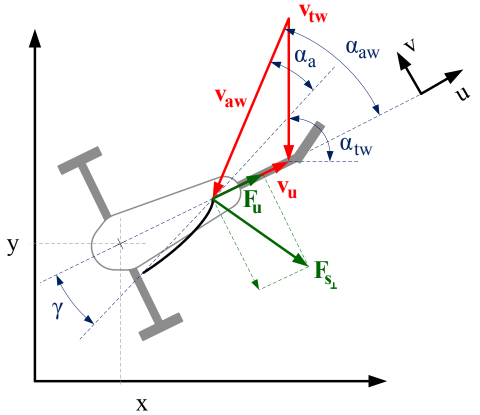

Fig. 2. Wind velocity triangle and aerodynamic forces

is the apparent wind angle denoted as α_{aw}. The apparent wind plays an essential role in sailing as it acts on the sail generating aerodynamic forces (in our "ideal" case the force $\mathbf{F_{s_\perp}}$). The absolute value of this force depends on $|\mathbf{v_{aw}}| = v_{aw}$, the sails properties (approximated by a proportional term d_s) as well as the angle of attack $\alpha_a = \alpha_{aw} - \gamma$. Thus

$$F_{s_\perp} = d_s \cdot v_{aw} \cdot \sin(\alpha_a). \tag{6}$$

Furthermore the apparent wind is responsible for the sailing vehicle being able to go upwind with a velocity up to two times faster than true wind velocity.

By using simple trigonometric relations, after decomposing $\mathbf{F_{s_\perp}}$ we obtain

$$F_u(v_u, \gamma, \psi) = d_s v_{aw}(v_u, \psi) \sin(\alpha_a) \sin(\gamma). \tag{7}$$

Since our task is to optimize velocity we would like to know the shape of our (cost) function to be maximized as well as the shape of the polar-performance-diagram of the underlying problem. This can be obtained by computing the equilibrium points of the system stated in Eqn. (4). Therefore we set $\dot{v}_u = 0$ and get the implicit function

$$f(v_u, \gamma, \psi) = F_u(v_u, \gamma, \psi) - d \cdot v_u = 0. \tag{8}$$

Figure 3 shows the surface of the above determined implicit function, where v_u is plotted together with γ and ψ.

In order to compute the polar-performance-diagram we have to establish v_{max} for a set of headings within the interval $[-\pi, \pi]$. According to different values for d we get the curves depicted in Figure 4. Roughly speaking Figures 3 and 4 represent the maps that we would like to search online in order to find their maximum i.e. to optimize the performance of the sailing vehicle. To do so, extremum seeking schemes will be used.

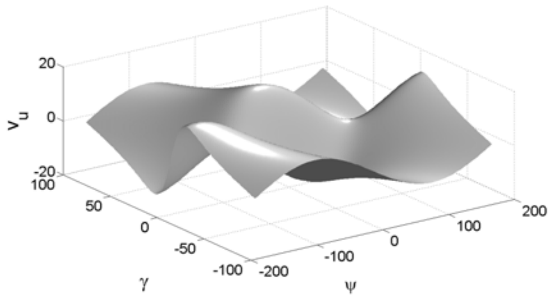

Fig. 3. Surface of the equilibrium map ($m = 150\ kg$, $d = 10$, $ds = 100$, $v_{tw} = 10\ m/s$, $\alpha_{tw} = \pi/2\ rad$ i.e. wind is coming from the north, $\gamma \in [-\pi/2, \pi/2]$, $\psi \in [-\pi, \pi]$)

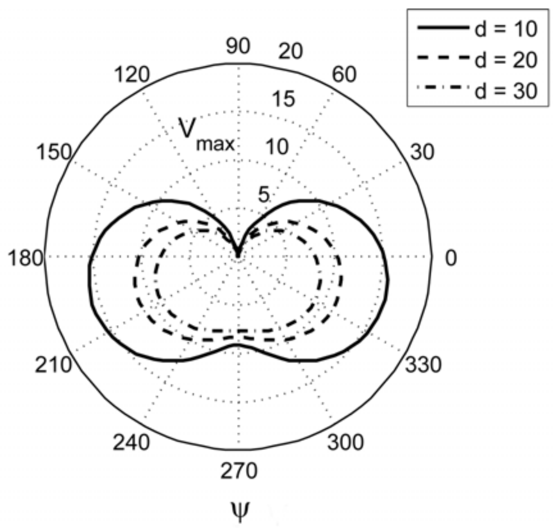

Fig. 4. Polar-performance-plot of dynamic model ($v_{max} = [m/s]$)

3. ONLINE SAIL OPTIMIZATION WITH EXTREMUM SEEKING

Before we go on with the application to sail optimization, let us recall a few basics of extremum seeking, loosely following [4], applied to the online optimization of a parabolic function, given by

$$g(\theta(t)) = g_0 + \frac{g_2}{2}(\theta(t) - \theta^*)^2, \tag{9}$$

where g_0 as well as g_2 are unknown constants. Note that the function $g(\theta)$ is convex (g_0 is the functions minimum) for all $g_2 > 0$ and concave (g_0 is the maximum of the function) if $g_2 < 0$. The term θ^* is the optimal, also unknown, parameter of the parabola. The aim of the extremum seeking algorithm is, through measuring the output $y(t) = g(\theta)$ of the system and changing $\theta(t)$, considered as the control input, to gradually find the optimum θ^*. Therefore the idea of the applied feedback-loop in Figure 5 is to remove unknown plant

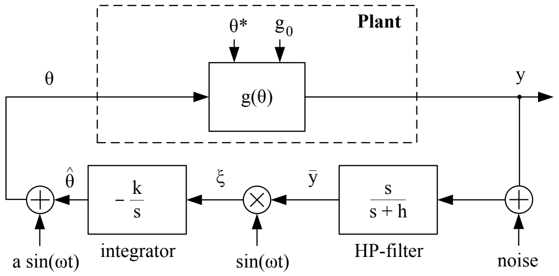

Fig. 5. Basic extremum seeking scheme for a static map (see [4])

parameters, in particular g_0, as it is typical to adaptive control approaches. Furthermore through the changes of θ one want to achieve that $(\theta(t) - \theta^*) \to 0$ so that the other unknown term namely $g_2/2$ disappears and consequently the output $g(\theta)$ of the system is driven to its extremum g_0. To do so, a basic extremum seeking scheme is composed of the following blocks, as pictured in Figure 5. To begin with, the system is excited by a sinusoidal signal $a\sin(\omega t)$ so that the output will span a part of the parabolic map. A high-pass filter is then used to get rid of the offset term g_0 (see $\bar{y}$ in Figure 5), giving variable $\bar{y}$. In the next step the signal is then multiplied by the sine wave $\sin(\omega t)$, resulting in the signal ξ which is, roughly speaking, composed of a linear term containing the parabolic shape term g_2, also related to the systems gradient; and a sum of sinusoidal signals. Finally a low-pass filter, represented by an integrator removes the sinusoidal signals to preserve only the gradient information. Stability conditions of this particular extremum seeking scheme have been obtained and were presented [10].

After this short introduction to the basic idea behind extremum seeking we now go on with applying the above scheme (see Figure 5) to our landyacht (see Eqn. (4) and (7)) in order to trim the sail angle γ in the best possible way to maximize surge for a certain heading ψ online. Hence, we consider γ as a control input for our landyacht. For simplicity we assume that ψ, v_{tw} and α_{tw} are constant. Similar to the above scheme in Figure 5, the idea is to explore the equilibrium map of our system through an excitation of the sail until the optimal parameter γ^* was found with the aid of the extremum seeking feedback-loop serving to extract the systems gradient information and thus driving the output v_u of the system to its maximum. Note that only measurements of the longitudinal velocity v_u are required. This is interesting since no information about wind speed or wind direction is needed. So the extremum seeking controller is capable of controlling our system with a minimum of knowledge.

However, our system is not a static map as the depicted one but a dynamic system. Accordingly we have to make sure that the system in particular the system in Eqn. (4) is exponentially stable [10]. Using contraction theory [11],[12] we could show that the Jacobian of the system is uniformly negative definite, i.e. that

$$\frac{\partial \dot{v}_u}{\partial v_u} = -\frac{d}{m} + \frac{1}{m} \cdot \frac{\partial F(v_u, \gamma, \psi)}{\partial v_u} < 0. \qquad (10)$$

Thus, the system is exponentially convergent. We then apply the basic extremum seeking feedback loop from Figure 5 to our system (substituting the "$g(\theta)$"-block). According to [10] our dynamic system can be thought of a static map if the frequency of the excitation signal ω is slow with respect to the plants dynamics. In order to provide accurate filtering it is obvious that the cut-off frequency h of the high-pass filter should be lower then ω which in fact means that the filter-section should be even more slowly. Due to that fact, the closed loop system should be designed to maintain the three time domains mentioned above.

On the practical side, guidelines for tuning the parameters of the different blocks, i.e. the cut-off frequency h of the high-pass filter, ω for the sinusoidal excitation signal with amplitude a and k for the gain of the integrator, were given in [4].

Following these design steps we parametrized the extremum seeking controller as follows. We chose $a = 0.01$, $\omega = 1\ rad/s$, $h = 0.7\ rad/s$, and $k = 2$, where the plants constants are $d = 10$, $d_s = 100$, $m = 150\ kg$, $L = 3\ m$, $v_{tw} = 10\ m/s$, $\alpha_{tw} = \pi/2\ rad$ (wind is coming from the north) and $\psi = 0\ rad$. In addition we added a noise term according to Figure 5 of the form $n\sin(\omega_n t)$ in order to simulate noise issues. The noise amplitude $n = 2a$ and the noise frequency $w_n = 1 \cdot 10^4 \cdot \omega$. The simulation results obtained with these parameters are depicted in Figure 6 where the black coloured curves display the transient response not affected by noise, while the blue ones show the systems behaviour if noise is present. In contrast the red lines illustrate the optimal tracking value of either optimal sail angle or maximum velocity.

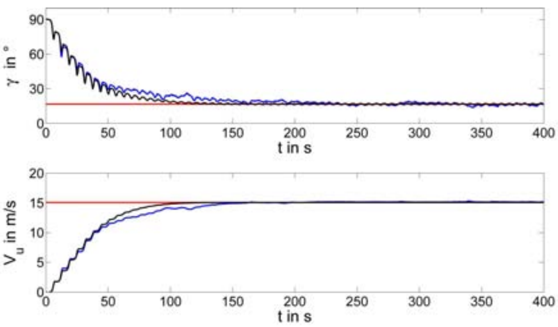

Fig. 6. Extremum seeking simulation results (black: undisturbed, blue: disturbed, red: optimal value)

Figure 7 shows both the theoretical computed polar-performance-diagram for the landyacht model (black) together with the results of the extremum search (red).

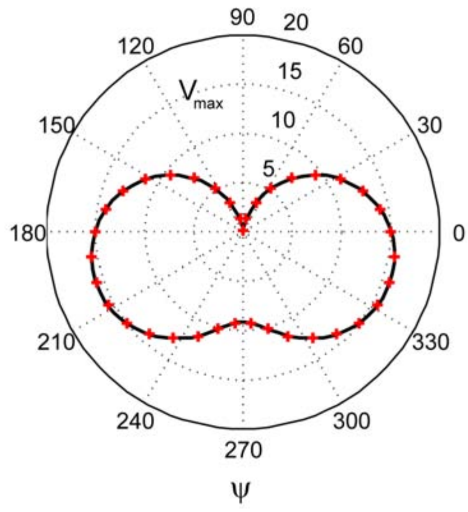

Fig. 7. Polar-performance-plot obtained by extremum seeking (red)

As one can see from Figure 6 and 7 the extremum seeking controller tracks the optimal values even if there is noise within approximately 2 minutes which is appropriate for a sailing vehicle.

The proposed controller could be used in conjunction with a motion planning or path generating algorithm that determines the heading whereas the controller tracks the optimal sail angle for the established heading.

4. ONLINE SAIL AND HEADING OPTIMIZATION WITH EXTREMUM SEEKING

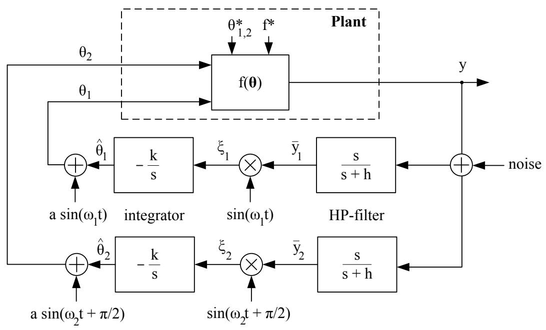

Fig. 8. Basic multi-parameter extremum seeking scheme for the two variable case (see [4]) with static function $f(\theta)$ and the optimum f^* of the function.

In the following section we propose a multi-parameter search where both sail and steering angle are controlled simultaneously in order to find the direction promising the best speed performance in addition to optimal sail-trimming. For the multi-parameter case we assume the dynamic system

$$\begin{pmatrix} \dot{v}_u \\ \dot{\psi} \end{pmatrix} = \begin{pmatrix} -\frac{d}{m}v_u + \frac{F_u(v_u,\gamma,\psi)}{m} \\ k_c(\psi_d - \psi) \end{pmatrix} \tag{11}$$

with the state $\mathbf{x} = (v_u \ \ \psi)^T$ and control input $\mathbf{u} = (\gamma \ \ \psi_d)^T$, where ψ_d is the extremum seeking parameter estimate and a set point for a cascaded controller controlling the front wheel angle at the same time. The system is contracting since the diagonal terms of the Jacobian of system (11), (12) can be shown to be uniformly negative definite and $\partial F_u / \partial \psi$ is uniformly bounded.

$$\frac{\partial f(\mathbf{x},\mathbf{u})}{\partial \mathbf{x}} = \begin{pmatrix} -\frac{d}{m} + \frac{1}{m}\frac{\partial F_u}{\partial v_u} & \frac{\partial F_u}{\partial \psi} \\ 0 & -k_c \end{pmatrix} \tag{12}$$

So we can apply multi-parameter extremum seeking. The multi-parameter scheme for the static two variable case is depicted in Figure 8.

From the Figure, one can easily see that the frequencies of the excitation signals have to be phase-shifted in order to track the optimum. Except that, the two loops can be designed identically as the one-dimensional case.

We chose the following parameters for our simulation: $a = 0.02$, $h = 0.2\ rad/s$, $\omega_1 = \omega_2 = 0.2\ rad/s$, $k = 0.3$, $k_c = 0.5$, where the plant constants remained the same, while the noise term was chosen to be $2a\sin(1 \cdot 10^4 \cdot \omega_1 t)$.

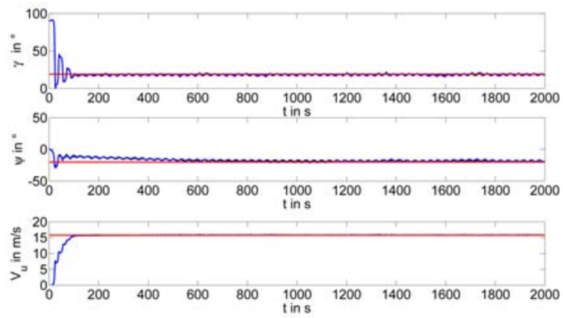

Fig. 9. Simulation results of the multi-variable extremum search (black: undisturbed, blue: disturbed, red: optimal value)

Figure 9 and 10 show the simulation results obtained for the multi-variable extremum search. One can see that the algorithm converges within a small distance towards the optimal values of γ and ψ maximizing the longitudinal velocity v_u. Also the red mark in the polar diagram illustrates that this is one of the two directions with best speed performance.

Another interesting aspect is that the transient response affected by noise nearly overlap exactly with the non affected response. Thus, the algorithm seems to be quite robust to noise. In a sense this can be understood by the fact that every perturbation of the system

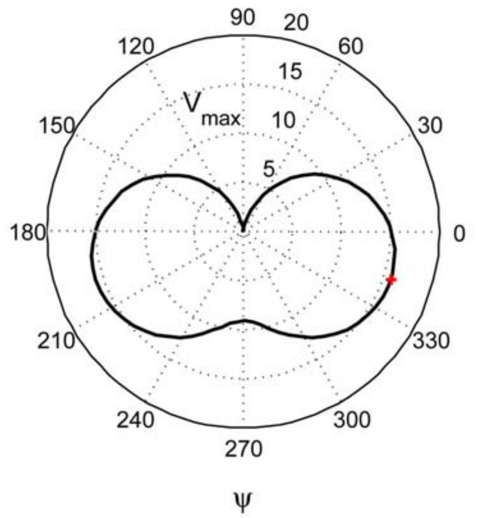

Fig. 10. One direction of best speed performance obtained from multi-variable extremum search

will help to explore the system and thus identify its gradient.

Similarly to the simulation results above the sail is trimmed to its best position within approximately 2 minutes, whereas the heading converges within approximately 10 minutes towards the final value. In terms of sailing vehicles both transient responses are appropriate.

5. CONCLUDING REMARKS

This paper presented a study on sail and heading optimization for a surface sailing vessel via extremum seeking control. The proposed model represents in a simple way the basic dynamics that are common to a wide variety of surface sailing vessels like landyachts, but also sailing boats. The proposed extremum seeking controllers are both capable of tracking the landyachts velocity in an appropriate time to its maximum either through sail or both sail and heading control. The algorithm is suitable for sailing purposes since it can cope with a minimum of knowledge in an adaptive non-model-feedback-based manner requiring measurements of the vehicles velocity only.

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