Autotuning Autopilots for Micro-ROVs

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***Abstract*—Underwater vehicles are highly nonlinear and complex systems, that makes designing autopilots extremely difficult. This paper presents autotuning as a method for tuning parameters of a micro-ROV autopilot. The main benefit of this procedure is that the model of the process does not have to be known. Autotuning is often used for industrial processes but not on marine vessels. This procedure, which is performed in closed-loop, is completely automated and enables the operator to retune an autopilot whenever ROV performance is degraded (due to different operating points, tether influence, currents, etc.). In this article we use already known different autotuning recommendations (primarily designed for Type 0 processes) with some modifications which we recommend for micro-ROVs. We also give results of using different types of PID controllers, whose parameters are being tuned. A real life demonstration on a VideoRay Pro II micro-ROV is provided.**

Keywords: autotuning, ROV, autopilot

I. Introduction

Micro-ROVs are underwater vehicles primarily used for underwater inspection and research of underwater habitats. In most of these situations, the operator is the one controlling the micro-ROV and the underwater currents that take the ROV off course present a great problem. The operator spends most of the time in getting the submersible to the site. During this process, the operator has to concentrate on the work that an autopilot can perform. With the help of an autopilot, submersible can be taken to the mission site without exhausting the operator. This article deals with autotuning methods for autopilots.

Autopilot tuning is the first step towards designing an autonomous system. In order to achieve a satisfactory trajectory following (planned off-line or on-line, Figure 1), a heading control problem should be solved adequately. Course-control belongs to the first hierarchical level of autonomous system control architecture (Figure 1). Design of heading control subsystem is difficult because of high complexity and 6-degree-of-freedom motion.

This article will limit its focus on micro-ROV heading control, with the assumption that the ROV is positioned at a constant depth, and that the forward speed is small and constant or equals zero (unless stated differently). On the other hand, submersibles are nonlinear systems and designing one unique controller with constant parameters that will ensure equal system behavior under different working conditions or different operating points is a difficult task. In addition to that, micro-ROVs are often used for underwater measurements and sample collection, therefore one micro-ROV is often equipped with different sensors. Moreover, the payload has great effect on system dynamics. Subsequently, a controller designed for a submersible carrying a certain payload, will not give satisfying performance for a different payload i.e. set of sensors. All problems mentioned here require a simple and fast procedure for tuning PID controllers when system dynamics change.

Autotuning PID controllers have been a matter of interest to many scientists, usually as a tool for tuning controllers in industrial processes: Åström and Hägglund in [3] proposed the idea to use relay feedback to tune parameters of PID controller automatically; Lee, Lee, Kwon and Park [4] used the method to automatically tune nonlinear pH controller. Other examples can be found in [5], [8]. Recommendations on tuning controllers are always based on an assumption that the controlled process is of a certain type: Chang et al. in [6] and Wang et al. in [7] presume FOPDT (first order process with dead time) type of systems, while Thyagarajan and Yu in [9] proposed autotuning for FOPDT, SOPDT (second order process with dead time) and higher order processes. Rarely are there in literature autotuning recommendations for marine vessels, i.e. Type 1 processes.

The theme of this article is automatic tuning of autopilot parameters for remotely operated micro submersibles in order to achieve heading-stabilization and heading following. Tuning methods are based on some known recommendations (Ziegler-Nichols) with slight modifications appropriate for use on Type 1 systems. These methods were used on a real system (VideoRay Pro II ROV) because they do not require knowing mathematical model of a system (it is either difficult to identify, or it is working under different payload or working conditions). The article is organized as follows: section II gives brief description of self-oscillations effect and describes implemented algorithm; section III gives different experimental results, while section IV concludes the paper.

II. Theoretical Background and Algorithm Description

A. Closed-loop oscillations

Recording the open-loop system response is one way to identify approximate system dynamics and tune a

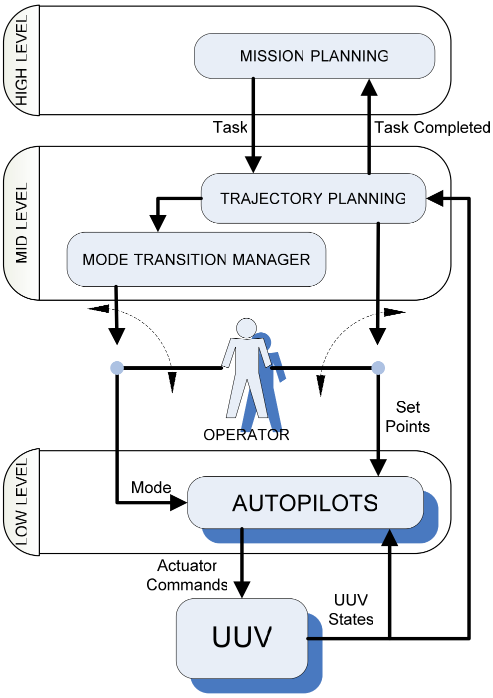

Figure 1. Control hierarchy

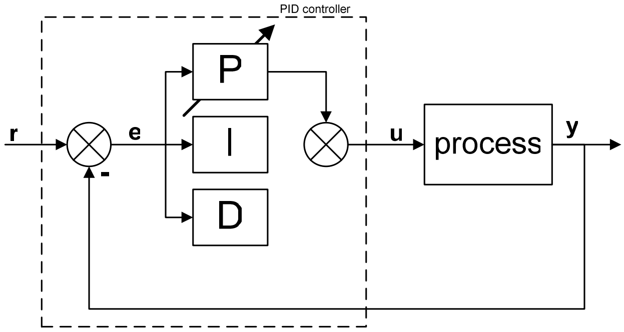

Figure 2. Obtaining stability margin with PID controller

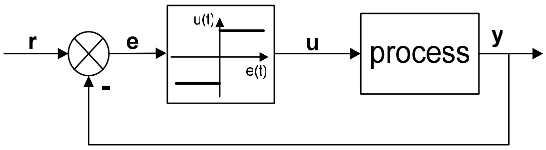

Figure 3. Obtaining limit-cycle with on-off controller

controller in order to achieve desired closed-loop dynamics. This approach is appropriate for Type 0 systems that are open-loop BIBO stable. This is not the case with submersibles since their course-control system can be approximated with Type 1 process, i.e. open-loop BIBO unstable process. For this reason we perform closed loop experiments, which limit process output.

Closed-loop experiments are based on forcing the system to oscillations: either by getting the system to stability margin or forcing it into limit-cycle regime. Stability margin can be obtained by tuning the P part of a PID controller (with derivative and integral channels turned off), as shown in Figure 2.

When the system is brought to oscillations, the oscillation parameters are recorded: the gain K_u of the P part of the controller that caused marginal stability and the period T_u of oscillations. These parameters give us the possibility to tune controller parameters according to one of known recommendations. All in all, this procedure is not suitable because getting the system to stability margin can result in an accidental switching to unstable regime. Furthermore, control signal might become oscillatory i.e. overloading of the actuators. This is the reason why we opted for the limit-cycle method.

Limit-cycles, in nonlinear systems, often present unwanted behavior, but in some cases they are intentionally caused by introducing a nonlinear element (on-off controller, relay, etc.) as shown in Figure 3. Components of the closed-loop system can be separated into a nonlinear part represented with the describing function G_N and the linear part G_L. Harmonic linearization is often used for describing nonlinear elements, wherein G_N is a function of the input sine amplitude E_m, i.e. $G_N(E_m)$.

Figure 3 implies that $r - y(t) = G_L(p)F(e, pe)$ where $p = \frac{d}{dt}$ is the derivation operator, $G_L(p) = \frac{B(p)}{A(p)}$ the transfer operator for the linear process part, and $F(e, pe)$ the describing function of a nonlinear element. Let the input signal $r(t) \approx const.$, which is a valid assumption since the experiment is performed with constant heading reference. Generally speaking, limit-cycle is asymmetric (because of constant input, [2]),

$$e(t) = e^0 + E_m \sin \omega_u t = e^0 + e^*$$

where:

e^0 – bias caused by the constant reference input

e^* – is the periodic component of the input signal to nonlinear element $e(t)$, obtained as the result of established self-oscillations in the nonlinear system. Since autotuning recommendations are given under the assumption that limit-cycles are symmetric, here we provide proof that Type 1 (or higher) systems (underwater vehicle heading control) give symmetric oscillations even if constant reference (heading) is present.

Theorem:

A constantly excited system composed of a symmetric nonlinear element and a Type 1 (or higher) process, produces symmetric oscillations at the input of a nonlinear element.

Proof:

For a system described above stands that

$$A(p)e + B(p)F(e, pe) = A(p)r = M^0 \quad (1.1)$$

Fourier series development of static nonlinearity F gives

$$F(e) = F^0(e^0, E_m) + P(e^0, E_m)e^* + Q(e^0, E_m)e^* \quad (1.2)$$

$$F^0(e^0, E_m) = \frac{1}{2\pi}\int_0^{2\pi} F(e^0, E_m \sin \omega t)d(\omega t)$$

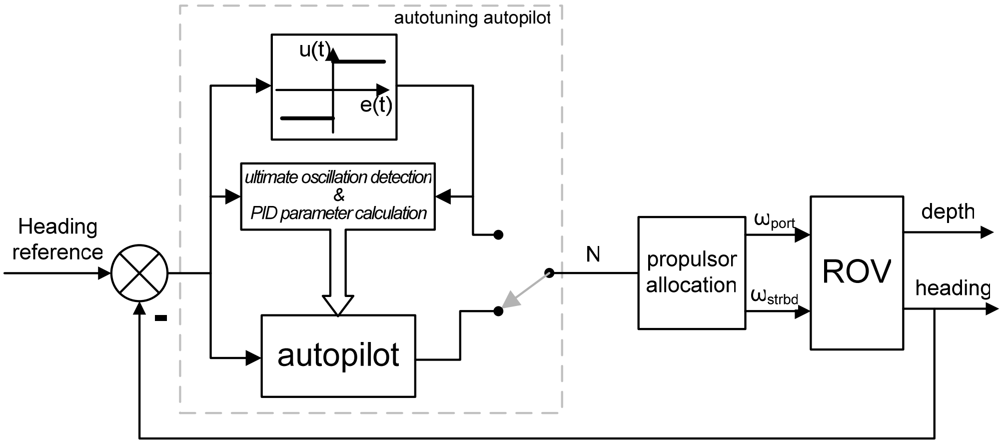

Figure 4. Scheme of autotuning procedure

$$Q(e^0, E_m) = \frac{1}{\pi E_m}\int_0^{2\pi} F(e^0, E_m \sin\omega t)\cos(\omega t)d(\omega t)\cdot$$

Hence, combining (1.1) and (1.2) gives two equations (static and dynamic)

$$A(0)e^0 + B(0)F^0(e^0, E_m) = M^0$$

$$A(p)e^* + B(p)\left[P(e^0, E_m) + \frac{Q(e^0, E_m)}{\omega}p\right]e^* = 0$$

Under the assumption that the process has at least one integrator, i.e. $A(0)=0$, follows that the following must be satisfied:

$$B(0)F^0(e^0, E_m) = 0$$

$B(0)$ equals zero if and only if there are zeros at the origin of the Laplace plane. In that case, they can be cancelled with poles from the origin (pole-zero cancellation is allowed because we are interested in global system behavior).If there are more zeros, which cannot be cancelled, that implies that the process is Type 0, which is contradictory to the initial assumption. From this it follows that (1.3) must be fulfilled:

$$F^0(e^0, E_m) = \frac{1}{2\pi}\int_0^{2\pi} F(e^0, E_m \sin\omega t)d(\omega t) = 0 \quad (1.3)$$

With the assumption of symmetrical nonlinear element, equation (1.3) will be valid if and only if $e^0=0$. This proves the statement. QED

From the theorem it follows that

$$F(e) = P(E_m) + jQ(E_m)$$

$$P(E_m) = \frac{1}{\pi E_m}\int_0^{2\pi} F(E_m \sin\omega t)\sin(\omega t)d(\omega t)$$

$$Q(E_m) = \frac{1}{\pi E_m}\int_0^{2\pi} F(E_m \sin\omega t)\cos(\omega t)d(\omega t)\cdot$$

For the on-off controller type nonlinearity, we obtain following parameters:

$$Q(E_m) = 0$$

$$F(E_m) = P(E_m) = \frac{4C}{\pi E_m}$$

Now it can be said that the equivalent gain K_u that caused self-oscillations is $\frac{4C}{\pi E_m}$.

B. *Autotuning procedure*

Figure 4 gives the idea of autotuning procedure. At the particular moment when we want to set new PID controller parameters (because behavior of the system has worsened; system parameters have changed or this is the first time they are being set), the operator switches to autotuning mode (switch in Figure 4 in upper position). This regime brings the system into self-oscillations using an on-off controller whose algorithm is given with

$$u(t) = \begin{cases} C, & \forall e(t) \geq 0 \\ -C, & \forall e(t) < 0 \end{cases}.$$

Now magnitude E_m of self-oscillations and their frequency ω are determined. Frequency of self-oscillations can be determined by observing the switching times of the on-off controller. Let us suppose that the on-off controller has switched at points t_1, t_2 and t_3 consecutive in time. When $t_2-t_1=t_3-t_2$ is fulfilled, we can affirm that the period of self-oscillations is $T_u=t_3-t_2$. Magnitude of self-oscillations can be determined by looking for maximal (y_{max}) and minimal (y_{min}) output value y in time period between t_1 i t_3. Then the self-oscillations magnitude is given with $E_m = \frac{y_{max} - y_{min}}{2}$.

Since in real systems the output signal is noisy, magnitude of self-oscillations can be determined more precisely if we take more sequential periods after moment $t_2-t_1=t_3-t_2$ occurs, calculate mean values of maximal ($\overline{y}_{max}$) and minimal ($\overline{y}_{min}$) values obtained, and use this data to determine magnitude of self oscillations according to $E_m = \frac{\overline{y}_{\max} - \overline{y}_{\min}}{2}$. With the two parameters evaluated, we follow through to the controller parameter determination, (as described in the following section). Once this is performed, the controller is switched back into closed-loop mode (switch in Figure 4 in lower position).

C. *Tuning recommendations*

One of most popular parameter tuning methods are those of Ziegler and Nichols (Table II) based on the closed-loop experiment and the quarter decay ratio criterion, [10]. Many other recommendations are mentioned in [1].

TABLE I
ZIEGLER-NICHOLS TUNING RECOMMENDATIONS

Ziegler-Nichols			
CONTROLLER TYPE	**K**	**T_I**	**T_D**
PI	0.45 K_u	0.833 T_u	-
PID PARALLEL	0.6 K_u	0.5 T_u	0.125 T_u
PD	0.4 K_u	-	0.05 T_u

These recommendations are not based on Type 1 or higher processes. It has been experimentally proven that satisfactory results for underwater vehicle heading control can be obtained by using half the value of the calculated proportional gain of the autopilot. This modification is used from this point on and is given in table II.

TABLE II
RECOMMENDED TUNING PARAMETERS FOR ROVS

CONTROLLER TYPE	**K**	**T_I**	**T_D**
PI	0.225 K_u	0.833 T_u	-
PID PARALLEL	0.3 K_u	0.5 T_u	0.125 T_u
PD	0.2 K_u	-	0.05 T_u

III. EXPERIMENTAL VERIFICATION

A. *ROV Characteristics*

The vehicle used for testing autotuning algorithms is the VideoRay Pro II micro submersible. Its dimensions are 355mm x 228mm x 215mm and it weighs 3.5kg. It is driven by port, starboard and vertical propulsors, which makes it an underactuated system. Heading control is accomplished by generating yaw moment N which is realized with the port and starboard thrusters. Heading sensor is a magnetic compass with 2° quantization. The vehicle is connected to the control board with a tether that causes substantial disturbance that should be compensated.

B. *PID Controllers*

The controllers used for heading autopilots are of PID type. Many different controllers have been tested. PID algorithms implemented are as follows:

- The PID controller using backward rectangular method (controller no. 1)

$$u(k)=q_0 e(k)+q_1 e(k-1)+q_2 e(k-2)+u(k-1)$$

$$q_0=K_P(1+\frac{T_s}{T_I}+\frac{T_D}{T_s});\quad q_1=-K_P(1+2\frac{T_D}{T_s});\quad q_2=K_P\frac{T_D}{T_s}$$

- The PI controller (controller no. 2)

$$u(k)=q_0 e(k)+q_1 e(k-1)+u(k-1)$$

$$q_0=K_P(1+\frac{T_s}{2T_I});\ q_1=-K_P(1-\frac{T_s}{2T_I})$$

- The PID controller - Åström's modification (controller no. 3)

$$u(k)=u_{PI}(k)+u_D(k)$$

$$u_D(k)=K_P\frac{T_D\alpha}{T_D+T_s\alpha}\left[y(k-1)-y(k)\right]+\frac{T_D}{T_D+T_s\alpha}u_D(k-1)$$

$$u_{PI}(k)=K_P\left[y(k-1)-y(k)\right]+\frac{K_P T_s}{2T_I}\left[e(k)-e(k-1)\right]$$

$$+\beta K_P\left[r(k)-r(k-1)-y(k)\right]+u_{PI}(k-1)$$

where $\alpha\in(3,20);\ \beta\in(0,1]$.

- The PID controller using backward rectangular method, approximating the derivation with a four-point difference (controller no. 4)

$$u(k)=K_P\Big\{e(k)-e(k-1)+\frac{T_s}{T_I}e(k)+$$

$$\frac{T_D}{6T_s}\left[e(k)-e(k-1)-6e(k-2)+2e(k-3)+e(k-4)\right]\Big\}+u(k-1)$$

C. *Experimental results with autotuning experiments*

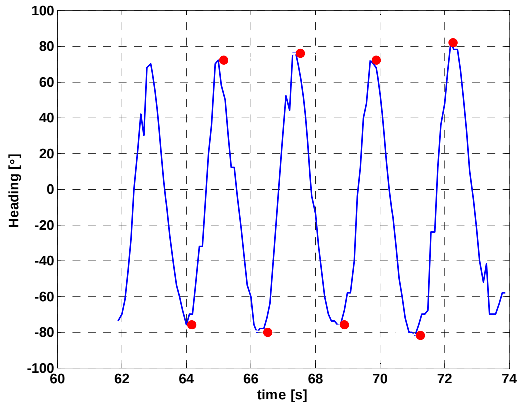

Figure 5. Unbiased form of established limit-cycle

Figure 5 shows the established oscillations during the autotuning experiment. The limit-cycle is given in its unbiased form. Dots mark maximal and minimal values of the oscillations. This set of data was used to calculate controller parameters.

D. *Heading control results*

The following figures display results with different types of controllers tuned according to the presented autotuning procedure. The first graph displays the reference heading (red dashed line) and the system response (blue solid line) in degrees. The second graph presents controller output that is in fact the reference signal to the starboard and port thrusters (blue line). The third graph gives the difference between the reference and the system output (magenta line).

In the following set of figures, the step reference was changed from the initial value of 40 to the final value of 180. Controllers 1, 3 and 4 were used for experiments with step reference change, while controllers 2, 3 and 4 are used for the triangle reference signal.

Figures 6 and 7 display the responses with the PID controller using backward rectangular method and the same PID controller but with derivation approximated with a four-point difference, respectively.

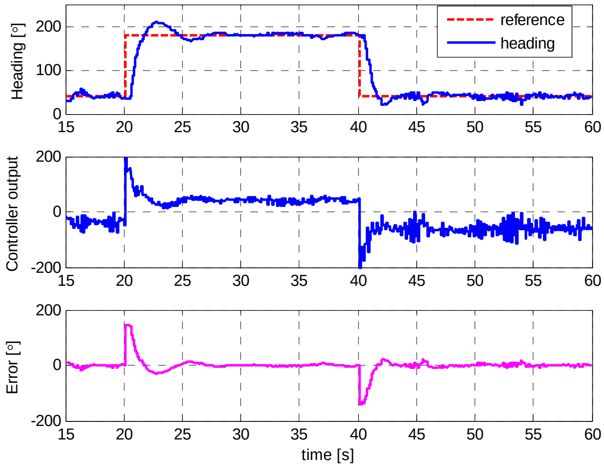

Figure 6. Results with controller no. 1

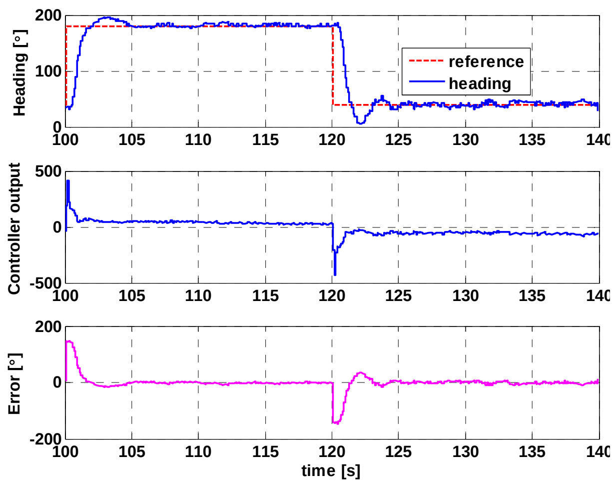

Figure 7. Results with controller no. 4

Both results are satisfactory with almost the same response time. One thing that should be noticed is the peak in controller output when using controller no. 4. This peak occurs due to stronger derivative influence in controller no. 4, and it forces the controller output value to double the maximal value of that with controller no. 3. This is rarely acceptable because it contributes to thruster overload.

Figures 8, 9 and 10 display the results with the PID controller with Åström's modification. This modification requires the additional tuning of two parameters. Increase of parameter β causes greater influence of the proportional channel, making response a bit faster but with a greater overshoot (figure 7). Figure 10 depicts the situation wherein parameter α is increased.

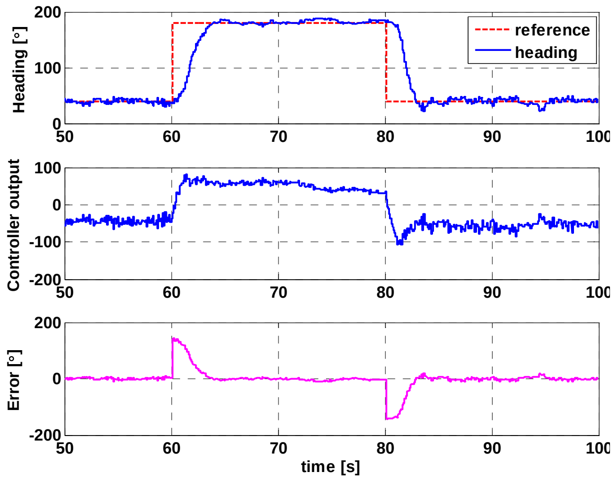

Figure 8. Results with controller no. 3 (α=3; β=0.1)

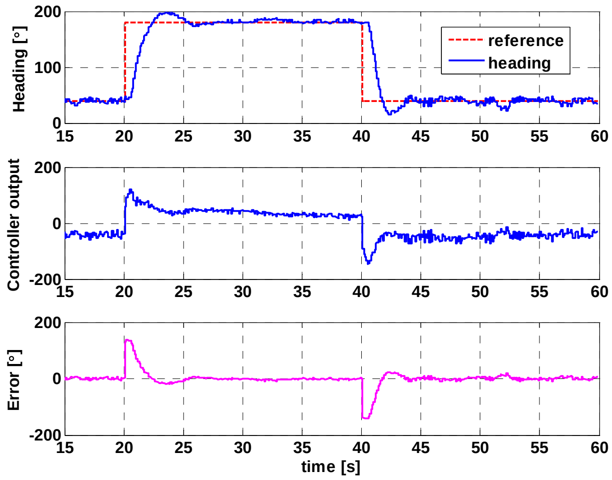

Figure 9. Results with controller no. 3 α=3; β=0.8

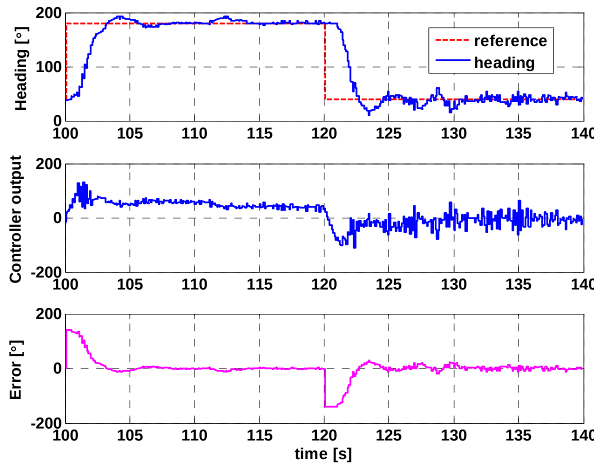

Figure 10. Results with controller no. 3 α=19; β=0.1

It is obvious that this increase gives greater weight to the derivative channel making the response noisier than acceptable. This analysis leads to the conclusion that for simpler applications, the PID controller using backward rectangular method gives quite satisfactory responses. However, if the operator wishes to tune parameters additionally, PID controller with Åström's modification is advised.

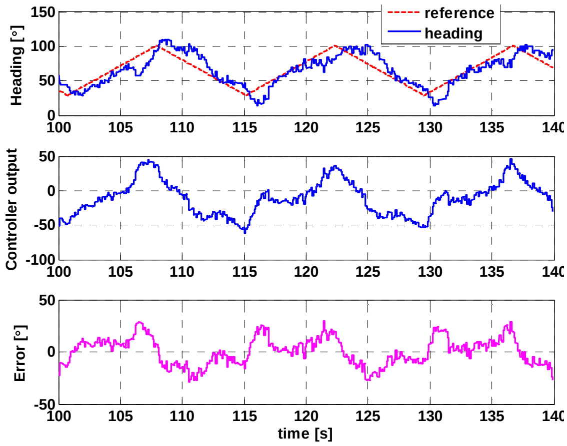

Figure 11. Results with controller no. 2

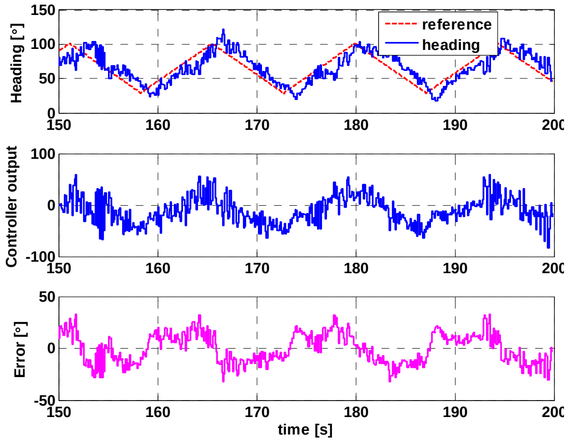

Figure 12. Results with controller no. 3 α=3; β=0.1

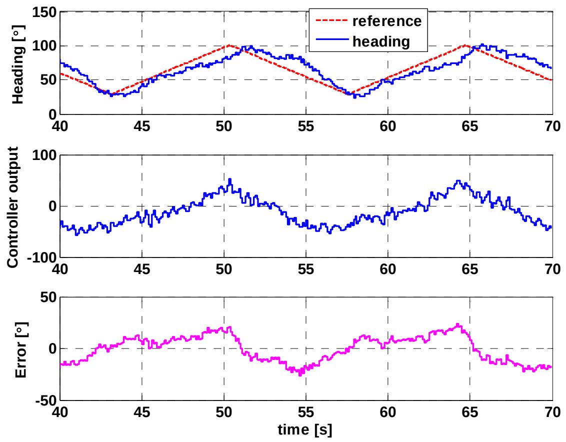

Figure 13. Results with controller no. 4

Figures 11, 12 and 13 display the results when the triangle reference input is used. Figure no. 11 gives the response with the PI controller. The error is reasonably small and the controller output is smooth. Introducing the PID controller with Åström's modification forces thrusters to change motor speed too often (additional tuning of parameters α and β is needed). In this case controller no. 4 gives the best results with smooth control signals and error somewhat smaller than in the case with PI controller.

IV. Conclusion

This paper demonstrates how autotuning methods can be implemented for underwater vehicles. The results presented show that these methods give satisfactory heading behavior. The main advantage of this method is its simplicity and the possibility of fully automated controller tuning. Having this in mind, the operator can easily retune the controller parameters if the change of either the payload or the operating point worsens the heading response. Disadvantages of this method are the approximation and uncertainty in modeling the behavior of the system and lack of knowledge of the first-principles mathematical model of the dynamics.

Our further research will be based on finding new recommendations made specifically for heading control of underwater vehicles.

Acknowledgment

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