Technical system and control algorithms of the underwater vehicle Krab II

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Abstract

Underwater vehicle (UV) Krab II, the possession of the Maritime Technology and Informatics Faculty of TU of Szczecin, is being gradually equipped with various systems improving its performance, among other things with systems for automatic control of the course angle and the depth of the vehicle. In the paper there is described technical construction of the system, enabling application and verification of various modern control methods. Two among the four methods investigated by the authors, the robust and fuzzy controller of the UV are described in the paper.

1 Introduction

The underwater vehicle (UV) Krab II, shown on Fig.1, is the main element of the SWOT system built in Maritime Technology Faculty of Technical University of Szczecin. Its appropriation is to detect technical objects in water, to inspect them and to monitor their state. The UV Krab II was tested in many underwater applications.

Originally it was stocked with hand control system consisting of a control joystick, a course and depth sensor, an observation camera and a system for information transmission, processing and presentation on a monitor screen.

Observing the picture and the course/depth data on the screen the operator can manipulate the joystick and control potentiometers of the UV-propellers to generate the desired UV-movement. The hand control demands continuous attention of the operator and a great hand skill. It gives good results in the nearness of the investigated object. But on the way to the object, when no reference points are visible in the water, when the UV must move along a
certain space trajectory, it must be controlled automatically. At the present stage of work there was built a computer control system securing for stable UV-motion and constant course angle and depth.

![Underwater vehicle Krab II](image)

Figure 1: Underwater vehicle Krab II.

2 Description of the control system

To control its motion the UV Krab has 5 propellers: 2 longitudinal propellers along its X-axis, 2 transversal propellers along the Y-axis, and 1 vertical propeller along the Z-axis.

The longitudinal propellers give thrust forwards and backwards, the vertical propeller upwards and downwards, the transversal propellers starboards and port side. The transversal propellers are also used to generate the torque turning the UV clock - or counter - clockwise. The remote hand-control of the propellers is performed from the control desk with joystick and setting potentiometers. The propeller thrust is proportional to the joystick deflection and the potentiometer turning angle. The operator of the UV can go over from the hand - to automatic control. On the control desk there is located the control mode switch: hand control and automatic control.

Switching over to the automatic mode is possible only if the setting potentiometers of the course and the depth are in the position "0". Then the switching causes automatic stabilization of the UV on the current depth (or distance from the bottom) and on the current course. Turning the potentiometers out of the setting "0" causes going over back to hand control. The control system uses for depth stabilization signals from the press sensor and from the echo sounder giving the distance from the bottom and from the sea surface. For course stabilization it uses signal from the magnetic course sensor.

The task of the digital control system is calculation of control signals according to the control algorithms assumed and giving them over to the drive system which will secure the required precision of course and depth stabilization for wide range of disturbances.
The digital control system shown on Fig. 2 is based on a PC. For communication with the external part of the system there is used an input/output analog card served by the PC and a bus. The card is located inside the PC casing. On the card there are installed: analog/digital converters for the measurement signals, analog/digital converters for the setting potentiometers, input system for the work-mode switches, work-mode transmitter and digital/analog converters for the control signal. Signals from the measurement sensors on the UV pass along the cable to the power controller console. To the same console there are also passed the signals from the work-mode switches and signals from the setting potentiometers of the vertical and transversal propellers. To the power controller console there is also connected the input/analog output card of the PC.

![Control system block diagram](image)

**Figure 2: Control system block diagram.**

The software of the control system realizes the following basic tasks:

a) Service of the input/analog output card

The communication with the card is accomplished by 5 registers with addresses from $100_{10}$ to $104_{10}$, one of them being control register making, among other things, specification of the input/output channels, which are used for recording and read-out. Two of the 5 registers record and read out the data, and the remaining two ones read out the control mode (hand or automatic control) and information about possible changes of this mode.

b) Registration of the UV state and of the control signals

After starting the service of the input/analog output card the program begins registration of the current course and depth and control signals generated by the PC. The read out of the UV state is accomplished by a procedure called...
out by software interrupt IC\text{H}. This procedure is called at the end of each time update operation. It makes also counting of control signals and recording of all data into a buffer store. The read out and recording operations are accomplished in every time step, introduced in the configuration stage of the program.

c) Data presentation on the screen and recording on the disc
The program shows the read data on the screen in text or graphic form. Additionally all data are recorded on the disc as a binary file.

d) Data processing
After the service of the UV has been stopped, the program enables to review the earlier recorded data, in a text and graphical form. The program can also convert the data from binary to text form accepted by professional tools of data processing as e.g. calculation sheets.

e) Parameters setting for program and controllers.
Before starting the communication with the UV the step $T_S$ must be specified, at which the data will be read out and the controllers will make their calculations. There must also be specified the reference signals of the course and depth. The reference signals can be introduced as any function $f(x)$ or as a constant signal. There is choice between the robust PID-, fuzzy PID-, and adaptive PID-controller cooperating with a fuzzy knowledge base about the plant. Some parameters of the control systems, as the reference course or controller settings can be modified in every moment.

3 Control algorithms

The UV Krab II is difficult to control [5] because of its strongly nonlinear dynamics and parameters variability according to the motion speed and direction (possible directions: forward, backward, port and starboard). UVs are influenced by sea currents, cable forces and other disturbances. The propellers have nonlinear steady-state characteristics saturation and with hysteresis. The Institute of Informatics of TU Szczecin investigates the motion dynamics and control methods of UVs. The investigations results are practically verified with the UV Krab II and are subject of 3 dissertations. In this paper there will be presented the robust and the fuzzy course control of the UV. There is also investigated the adaptive control with fuzzy-knowledge base and neural RBF-memory control.

3.1 Robust control
The UV, both as a course control and as a depth control plant, can be described with complicated nonlinear differential equations [5]. In controller designing one uses usually linear approximations of the nonlinear motion models as transfer functions. They are easier to identify experimentally. The course and depth transfer function of the UV has the form:

$$G(s) = \frac{y(s)}{x(s)} = \frac{K}{s(sT + 1)}$$
where: \( y \) - course angle/depth \( K \) - gain
\( x \) - torque/thrust \( T \) - time constant

The coefficients \( K \) and \( T \) are variable and depend on the speed and movement direction, on the load and external disturbances. Because their variations can be significant there was a robust PID controller applied, which can tolerate such variations. The robust controller must satisfy the robust stability condition (2) which ensures the stability when the plant characteristic vary in a certain range [4]:

\[
\sup_{\omega} \left| \eta_m(\omega) \right| < 1
\]

where: \( \eta \) - complementary sensitivity function (transfer function of the closed control system) and \( \eta_m \) - the maximal value of the multiplicative plant uncertainty. The uncertainty \( \eta_m \) can be calculated from:

\[
\eta_m = \frac{I_a}{|G_o|}
\]

where: \( I_a \) - additive plant uncertainty and \( G_o(f) \) -nominal transfer function of the plant. The plant uncertainty is illustrated by Figure 3.

As nominal transfer function there was assumed for the course stabilization the function \( G_f(s) \) which was identified experimentally [9] at zero longitudinal speed of the UV, and for the depth stabilization the transfer function \( G_z(s) \) identified for the vertical speed \( w=0 \).

\[
G_f(s) = \frac{\psi(s)}{M(s)} = \frac{0.021929}{s(1 + 0.30372s)} \left[ \frac{\text{rad} \cdot \text{s}}{N \cdot m} \right]
\]

\[
G_z(s) = \frac{z(s)}{Z_p(s)} = \frac{0.0055481}{s(1 + 0.65423s)} \left[ \frac{m \cdot \text{s}}{N} \right]
\]

where: \( \psi \) - course angle \( M \) - driving torque
\( z \) - depth of the UV \( Z_p \) - vertical thrust
The maximal plant uncertainty \( \bar{l}_a \) was assumed to be 99% of the real part of the nominal characteristic \( \bar{l}_a = 0.99 \text{Re}[G(e^{j\omega})] \).

The second condition which must be satisfied by robust control system is the robust performance condition (5) which ensures certain assumed minimal system performance even at greatest assumed difference between the real and nominal plant transfer function.

\[
|\eta| + |\varepsilon| < 1
\]

(5)

where:
- \( \eta \) - sensitivity function of the control system
- \( \varepsilon \) - the greatest disturbance influencing the system

The transfer function of the PID-controller:

\[
G_{R}(s) = K_C \cdot (1 + sT_D + \frac{1}{sT_I})
\]

(6)

Analytical transformations give formulas showing the dependence of the controller parameters on the parameter \( \lambda \) being the time constant of the closed control system [5]:

\[
K_C = \frac{2\lambda + T}{K\lambda^2} \quad T_I = 2\lambda + T \quad T_D = \frac{2\lambda T}{2\lambda + T}
\]

(7)

The synthesis of the robust controller was made [9] with computer simulations. The aim was to find such a value of \( \lambda \) which would satisfy the robust stability (2) and robust performance condition (5). The simulations gave few sets of the controller parameters satisfying the conditions (2) and (5). E.g. the depth controller can have the following parameters:

\( K_C = 382.292 \quad T_I = 3.054 \quad T_D = 0.514 \quad \text{at} \ \lambda = 1.2 \)

Possible course controller parameters are:

\( K_C = 135.645 \quad T_I = 1.904 \quad T_D = 0.255 \quad \text{at} \ \lambda = 0.8 \)

Figure 4: Scheme of the robust digital PID-controller with anti-windup.
Because the static characteristic of the UV propellers show torque and thrust saturations \( (M_{\text{max}}, M_{\text{min}}, Z_{p_{\text{max}}}, Z_{p_{\text{min}}}) \) there was the antiwindup [4] applied in the controllers. It influences positively the stability and performance of the control systems. Fig. 4 shows final PID-controller scheme in its digital version. It has shown its practical usefulness for the UV stabilization.

3.2 Fuzzy depth and course control

Robust controller give great tolerance for dynamics variations of the UV taking place in various work conditions. However this tolerance is achieved at cost of the control performance. There exist a potential possibility to improve the control performance with application of fuzzy controllers. For the Krab II there was designed on the base of [2] the fuzzy PID-controller shown on Fig. 5.

![Diagram of fuzzy PID-controller](image)

Figure 5: Scheme of fuzzy PID-controller for the UV Krab II.

The performance of this controller applied to the UV was investigated in the first stage with computer simulation in the works [3] and [8]. The controller parameters were in these investigations specified with trial and error method. Because of this reason the results cannot be considered to be optimal. The mentioned investigations have shown [6] that the fuzzy controller gives better performance than the robust one, but it causes very violent (often having no logical reasons) action and many overswitchings of the UV propellers. An example of propellers action with the first worked-out fuzzy controller shows Fig.6.

Parameters specification of a 3-input fuzzy PID-controller is a very difficult task because the controller has 8 degrees of freedom/parameters which values are to be specified. One-and two-input fuzzy P-, PI- and PD-controllers can be designed on the base of the man operator experience attained from the UV hand-control. This experience is formulated in form of inference rules.

In the instance of the fuzzy PID-controller the man operator would have to control the UV propellers on the base of observations of 3 variables: \( e, \dot{e}, \int e \, dt \), which is impossible for one man. Therefore the parameters specification for the fuzzy PID-controller must be made with special methods.
One of the possibilities is transformation of the fuzzy controller in a neuro-fuzzy network [7]. This network can be then automatically learned to act similarly like the man operator. Using the error back propagation method the neuro-fuzzy PID controller will find its "good" parameters. The condition for transformation of a fuzzy PID in a neuro-fuzzy PID-controller is conversion of noncontinuously differentiable fuzzification, inference (max. and min. operators), and defuzzification units in continuously differentiable neurons which can be adapted with the error back-propagation method. For fuzzy/neuro-fuzzy conversion there were used methods given in [7] and own ideas.

The neuro-fuzzy PID controller is subject of investigations made by the authors within the grant Nr 21-0119/1788-00 of TU Szczecin. Because of the volume limitation of this paper the authors don't give here father details of the controller. This will be done in next publications. There are also made investigations on application of the RBF*-memory in modelling of units and controller synthesis for UV (the grant Nr 000-0603/17-00-00 of TU Szczecin).

*RBF - radial basic function.

REFERENCES


