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Tuning of PID Controller Using IC Algorithm for a Capsubot Robot

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Abstract—In this paper the optimal value of parameters of PID controller were obtained using imperialist competitive algorithm (ICA). The five cost functions were selected: ISE , $ITSE$, IAE , $ITAE$ and I_F . These functions were used in ICA as objective functions. Results from ICA were applied in the control scheme for legless capsubot robot. They were presented on figures and compared with each other.

1 I. INTRODUCTION

MICRO-ROBOTIC systems are small-sized robots used in a sensitive environment, such as the human body, for diagnosis and inspection. Moreover, they can be used in confined environments during pipeline inspection, engineering diagnostics, seabed and disaster exploration etc. Micro-robots, often called capsubots, usually consist of an inner mass and an outer body. Conventional motion systems have been designed and used by mimicking the progress of earthworms [1] and canoe rowing [2], magnetic field [3] etc. The principle of internal force of static friction is well known and described [4]. The main idea is that directional movements can be achieved by a vibration driven internal mass / inertia that interacts with the main body of the robot and indirectly overcomes environmental resistance forces [5], [6].

One of the main tasks is to follow the given trajectory by the robot. Second the main aim is control system designing with different types of controllers. For this reason, many works on trajectory and control systems design can be found in the literature. In the paper [7] authors investigated the motion of the capsubot and presented four-step motion strategy. The optimal control law derived from capsubot locomotion was shown and discussed. Obtained theoretical results were validated by real capsubot for one-dimensional motion. Authors of [5] analyzed the trajectory control of underactuated class of the capsubot. The presented results based on the two-stage control strategy. Obtained trajectory controls were developed for an underactuated one-dimensional, two-dimensional and 1 hybrid two-dimensional capsubots with four operating modes. The discussed two-stage control system was unique for this type of robot. Besides, the studying shown the improved model simulation and experimental validation of the proposed trajectory tracking control along with their analyzes and discussion. The paper [8] contains the model of underactuated

1 one-dimensional internal mass reaction capsubot with four-step motion profile. The authors also presented the simulation results and analyzed them. For the same model of capsubot with four-step motion strategy, authors of [9] performed the control using modified chaotic genetic algorithm and analyzed the results of simulation. The article [10] focused on the proposed strategy for optimizing the capsubot movement and therefore minimizing energy consumption, in order to reduce the capsubot size for clinical feasibility. The implementation of the assumptions required the use of proposed five-step motion strategy. Also, the article contains comparison of three motion profiles and applied non-linear optimization method to validate details of optimum motion per each motion profile. In [11] authors used similar underactuated model of the capsubot, presented seven-step motion strategy and analyzed tracking issue. Based on this motion profile, an iterative learning control was proposed with the scheme demonstrated from employing frequency domain using of Nyquist plot.

The presented paper is organized as follows. At the 1 first the notation considers fractional-order PID controller is presented. Next, mathematical model of capsubot robot is described and its a nonlinear dynamical system is shown by state space representation. Section IV consists a general description of imperialist competitive algorithm (ICA). Section V presents transfer functions of linearized model of capsubot robot, input vectors for ICA algorithm, method of approximation of fractional-order PID controller and chosen criterion for design of controllers. A few examples are shown in Section VI with a discussion of the obtained results. The last section includes a few concluding remarks.

1 II. MATHEMATICAL MODEL OF A CAPSUBOT

The concept of the construction of a micro-robot was presented in the papers [12], [13]. Without loss a generality, the movement of the robot, hereinafter referred to as the capsubot robot, is based on the movement of the actuator, which drives the internal pendulum. The pendulum moves forward and backward driving the entire system. The capsubot starts to move when the resultant force applied to the body in the horizontal direction exceeds the maximum value of the dry friction force on the contact surface. We assume that the mass of the pendulum is centralized in the sphere. Moreover, the center of mass of the platform coincides with the axis

of rotation. The kinematic scheme of capsutbot is shown on Figure 1.

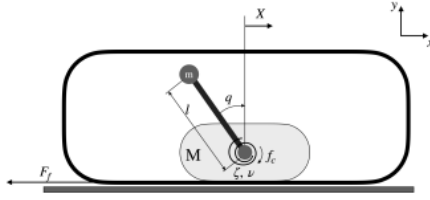


Fig. 1. The model of capsutbot robot [14].

Based on scheme, the position and velocity of the ball of pendulum are given as follows

$$\begin{aligned} x_b &= X - l \cdot \sin(q), & \dot{x}_b &= \dot{X} - l \cdot \dot{q} \cdot \cos(q), \\ y_b &= l \cdot \cos(q), & \dot{y}_b &= -l \cdot \dot{q} \cdot \sin(q). \end{aligned}$$

Let F_f be the resultant force applied on the ball which can be decomposed into the horizontal and the vertical direction. Directions of force F_f are described by the following formula

$$F_{f_x} = -m\ddot{X} + ml\ddot{q} \cos(q) - ml\dot{q}^2 \sin(q) + \frac{(\zeta q + \nu \dot{q}) \cos(q)}{l}, \quad (17)$$

$$F_{f_y} = mg - ml\dot{q}^2 \cos(q) - ml\ddot{q} \sin(q) - \frac{(\zeta q + \nu \dot{q}) \sin(q)}{l}.$$

The sliding friction force is given by the following form

$$f = \begin{cases} c(M + F_{f_y}) \text{Sign}(\dot{X}), & \text{for } \dot{X} \neq 0, \\ f_0, & \text{for } \dot{X} = 0. \end{cases}$$

with the sliding friction coefficient c .

Using the Euler-Lagrange formalism and assuming that $\dot{X}$ is greater than zero we can describe a dynamical model of capsutbot robot in the following form

$$\begin{aligned} ml^2 \ddot{q} - ml \cos(q) \ddot{X} - mgl \sin(q) + \zeta q + \nu \dot{q} &= u \\ -ml [\cos(q) + c \cdot \sin(q)] \ddot{q} + (M + m) \ddot{X} &+ \\ + ml [\sin(q) - c \cdot \cos(q)] \dot{q}^2 &+ \\ + c \left[(M + m)g - \frac{(\zeta q + \nu \dot{q}) \sin(q)}{l} \right] &= 0. \end{aligned} \quad (1)$$

Let us introduce constants

$$C_1 = ml^2(M + m) - m^2 l^2 \cos^2 q - m^2 l^2 \cos q \sin q, \quad (16)$$

$$C_2 = \sin q - c \cdot \cos q, \quad C_3 = \cos q + c \cdot \sin q,$$

$$C_4 = ml^3(M + m) - m^2 l^3 \cos^2 q - m^2 l^3 \cos q \sin q.$$

Then, we obtain

$$\begin{aligned} \ddot{X} &= \frac{mlC_3}{C_1} u - \frac{m^3 l^3 \cos^2 q C_2 C_3}{(M + m) C_4} \dot{q}^2 - \frac{m^2 l^2 c g C_3}{C_1} + \\ &+ \frac{m^2 l^2 c (\zeta q + \nu \dot{q}) \sin q}{(M + m) C_4} + \\ &+ \frac{m^2 l^2 g \sin q C_3}{C_1} + \frac{ml\zeta C_3}{C_1} q - \frac{ml\nu C_3}{C_1} - \\ &+ \frac{mlC_2}{(M + m)} \dot{q}^2 - cg + \\ &+ \frac{c\zeta \sin q}{l(M + m)} q + \frac{\nu \sin q}{l(M + m)} \dot{q}, \\ \ddot{q} &= \frac{(M + m)}{C_1} u - \frac{m^2 l^2 \cos^2 q C_2}{C_1} \dot{q}^2 - \\ &+ \frac{mlcg(M + m)}{C_1} + \frac{mlc\zeta \sin q}{C_4} q + \\ &+ \frac{mlc\nu \sin q}{C_4} \dot{q} + \frac{(M + m)mgl \sin q}{C_1} + \\ &+ \frac{\zeta(M + m)}{C_1} q - \frac{\nu(M + m)}{C_1} \dot{q}. \end{aligned} \quad (2)$$

Now, the second-order differential state equation given by (1) can be expressed by the equivalent first-order equations with the following state variables

$$x_1 = q, \quad x_2 = X, \quad x_3 = \dot{x}_1 = \dot{q}, \quad x_4 = \dot{x}_2 = \dot{X},$$

$$x = [x_1, x_2, x_3, x_4]^T.$$

Finally, the equation (1) is rewritten into a state space form, as a vector first-order nonlinear differential equations:

$$\dot{x} = F(x)x + G(x), \quad (4)$$

where:

$$F = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ A_1 & 0 & A_2 & 0 \\ A_3 & 0 & A_4 & 0 \end{bmatrix}, \quad G = \begin{bmatrix} 0 \\ 0 \\ A_5 \\ A_6 \end{bmatrix},$$

where

$$A_1 = \frac{mlc\zeta \sin q}{C_4} + \frac{\zeta(M + m)}{C_1},$$

$$A_2 = \frac{mlc\nu \sin q}{C_4} - \frac{\nu(M + m) - m^2 l^2 \cos^2 q C_2 \dot{q}}{C_1},$$

$$A_3 = \frac{c\zeta \sin q}{l(M + m)} + \frac{m^2 l^2 c\zeta \sin q}{(M + m) C_4} + \frac{ml\zeta C_3}{C_1},$$

$$A_4 = \frac{m^2 l^2 \nu \sin q - m^3 l^3 \cos^2 q C_2 C_3 \dot{q}}{(M + m) C_4} - \frac{mlC_2 \dot{q}}{(M + m)} + \frac{20 \sin q}{l(M + m)},$$

$$A_5 = \frac{(M + m)u - mlcg(M + m) + (M + m)mgl \sin q}{C_1},$$

$$A_6 = \frac{mlC_3 u - m^2 l^2 c g C_3 + m^2 l^2 g \sin q C_3 - ml\nu C_3}{C_1} - cg.$$

III. IMPERIALIST COMPETITIVE ALGORITHM (ICA)

The general description of ICA is presented below. The algorithm begins with an initial population called countries. A part of them which are the best countries in the initial population are selected and called imperialists and the rest from this population become the colonies of these imperialists. All of the colonies from the initial population are divided among the imperialists according to their power. The power of an empire is defined as inversely proportional to its cost. A set of parameters which will be optimized is called country and its dimension is equal to N_v . This set is represented by $country = \{p_1, p_2, \dots, p_{N_v}\}$. The cost function is defined by $cost = f(p_1, p_2, \dots, p_{N_v})$. Moreover, we denote by N_p size of the initial population, N_{imp} size of the most powerful countries selected to design the empires, N_c size of the population which will become colonies belonging to an empire. The normalized power of each imperialist is represented by

$$p_n = \frac{C_n}{\sum_{i=1}^{N_{imp}} C_i},$$

where $C_n = c_n - \max_i \{c_i\}$ is normalized cost of the n -th imperialist cost c_n . Additionally, the total power of an empire should be defined. This parameter is represented by formula

$$TP_n = Cost(imperialist_n) + \xi \text{mean}\{Cost(colonies_of_empire_n)\},$$

where TP_n is the total cost of the n -th empire and ξ is a positive number which is considered to be less than 1.

A detailed description of the imperialist competitive algorithm can be found in [15].

IV. CONTROL DESIGN

PID control is one of the most popular control scheme. A well-known mathematical formula for PID controller is given as follows

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{de(t)}{dt}, \quad (5)$$

where $u(t)$ is a control signal, $e(t)$ is a error signal (difference between input and output signal in a closed-loop control scheme), K_p , K_i and K_d are parameters of PID controller [16]. The transfer function for ideal continuous time PID controller has the form

$$G(s) = \frac{U(s)}{E(s)} = K_p + K_i \frac{1}{s} + K_d s. \quad (6)$$

The main aim of controllers is to track the desired parameter such as a trajectory of the capsutbot which are fixed by user. The capsutbot robot mathematical model described by equations (1) is nonlinear. Using Matlab S-Function method, linear model was obtained. Next, we get transfer functions which are represented in the following form

$$G_1(s) = \frac{Q(s)}{U(s)} = \frac{2500}{s^2 + 25680s + 65000} \quad (7)$$

$$G_2(s) = \frac{X(s)}{U(s)} = \frac{125s^2 + 1975000s + 5000000}{s^4 + 25680s^3 + 65000s} \quad (8)$$

with the parameters of capsutbot robot: $M = 0.008 \text{ kg}$, $m = 0.005 \text{ kg}$, $\zeta = 0.01$, $\nu = 0.5$, $l = 0.05 \text{ m}$, $c = 0.2$ and $g = 9.81 \frac{\text{m}}{\text{s}^2}$. The control scheme consists of the controller described by (5). Parameters of controller are optimized with ICA algorithm. The set of parameters of the PID controller given by formula (5) which will be optimized contains 3 variables

$$P_i = [K_{P_F} \quad K_{I_F} \quad K_{D_F}].$$

For the simulations the following performance criteria are selected as fitness functions:

IAE (Integral of Absolut Error) [17] described by the formula (9)

$$I_{IAE} = \int_0^T |e(t)| dt, \quad (9)$$

ISE (Integral of Squared Error) [18] given by (10)

$$I_{ISE} = \int_0^T e^2(t) dt, \quad (10)$$

ITAE (Integral of Time-weighted Absolut Error) [18] defined by (11)

$$I_{ITAE} = \int_0^T t|e(t)| dt, \quad (11)$$

ITSE (Integral of Time Squared Error) wyrażony wzorem (10)

$$I_{ITSE} = \int_0^T t e^2(t) dt, \quad (12)$$

and function

$$I_F = \min[a + \min(b) + \min(c) + \min(d)], \quad (13)$$

where a is a rise time, b is a settling time, c is an overshoot, d an undershoot [19].

The error $e(t)$ is the difference between the set point desired X for position of capsutbot shell and for position of the ball. Above-mentioned conditions are chosen as the objective function which is minimizing for the ICA algorithm. The algorithm runs until the optimal value of the parameters for fractional type of PID controllers are obtained according to the set conditions of the ICA algorithm.

V. SIMULATION RESULTS

All the simulations are provided with Matlab/Simulink environment. For transfer function given by (7) parameters of ICA algorithm are set as follows: the initial countries is 200, the initial imperialists is 10, a number of iterations is equal to 10, the maximum values vector of controller parameters is $V_{\max} = [5000 \ 10 \ 10]$ and minimum of its is $V_{\min} = [0 \ 0 \ 0]$.

Table I gives a summary of results from simulations with function (7).

For transfer function given by (8) parameters of ICA algorithm are set as follows: the initial countries is 100, the initial imperialists is 8, a number of iterations is equal to

TABLE I
RESULTS FOR THE TRANSFER FUNCTION GIVEN BY (7).

A criterion	Parameters of PID			Value of cost function
I_F	$K_P = 4746$	$K_I = 1.15$	$K_D = 0.83$	0.013
ITAE	$K_P = 949.5$	$K_I = 9.2$	$K_D = 5.73$	0.0258
IAE	$K_P = 2361$	$K_I = 0.4$	$K_D = 6.65$	0.0151
ISE	$K_P = 4645.6$	$K_I = 4.03$	$K_D = 5.9$	0.01
ITSE	$K_P = 3477.6$	$K_I = 8.4$	$K_D = 7.15$	5.0632

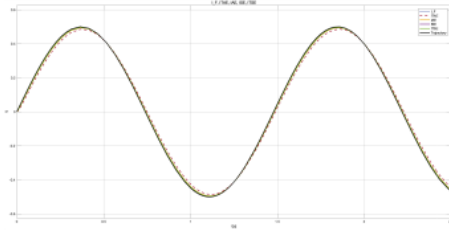


Fig. 2. Response with IAE criterion

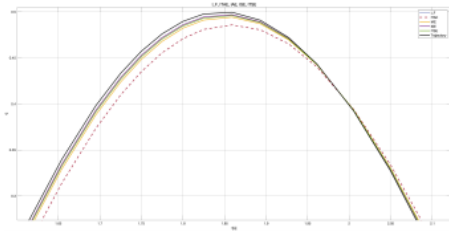


Fig. 3. Response with IAE criterion

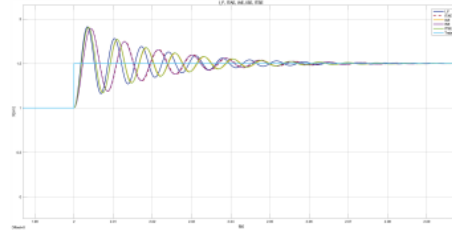


Fig. 5. Response with ITAE and I_F criteria

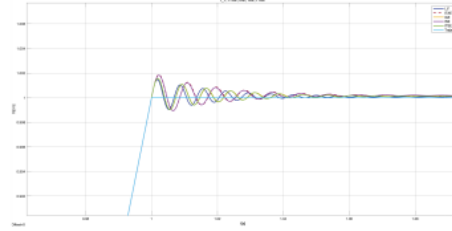


Fig. 6. Response with ITAE and I_F criteria

10, the maximum values vector of controller parameters is $V_{\max} = [1000 \ 100 \ 100]$ and minimum of its is $V_{\min} = [0 \ 0 \ 0]$.

Table II gives a summary of results from simulations with function (8).

Figures 2 and 3 are presented responses of dynamical system described by (7) with PID controller which parameters are obtained with all of the criterion. It can be concluded that the best results are obtained for ISE and I_F criterion as the cost functions. This fact is presented on Figure 3 with zoomed chart. The second remark is that the obtained PID parameters for all cost functions don't guarantee achievement of the desired set of value.

Figures 4, 5 and 6 are shown response of dynamical system

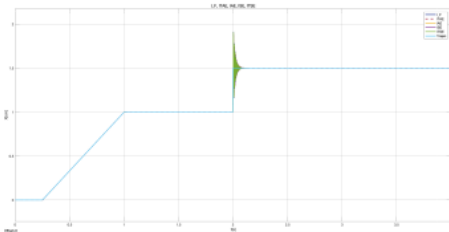


Fig. 4. Response with ITAE and I_F criteria

defined by (8). The nature of the all response is oscillatory. Comparing and analyzing Figures 5 and 6, it can be concluded that the best result was obtained for the criterion I_F . On the other side, the amplitude of the oscillations of the all responses is similar and the achievement of the set value is comparable.

VI. CONCLUSIONS

This paper presented a closed-loop control system for the special type of capsbot robot with PID controllers which parameters were obtained using imperialist competitive algorithm.

A comparative analysis is presented comparing the effectiveness of the use of the above-mentioned controllers with parameters received from ICA. The five cost functions were applied as cost function in ICA. After scrutinizing the best results were obtained for I_F cost function for both dynamical systems given by (7) and (8).

In the control approach the closed-loop system has to have the feedback with information about position capsbot robot. The embedded system of appropriate sensors is obligatory [20].

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TABLE II
RESULTS FOR THE TRANSFER FUNCTION GIVEN BY (8).

A criterion	Parameters of PID	Value of cost function
I_F	$K_P = 849.43$ $K_I = 61.1$ $K_D = 100$	0.0009
$ITAE$	$K_P = 345.1$ $K_I = 94.5$ $K_D = 65.3$	0.000000006
IAE	$K_P = 312.9$ $K_I = 29.4$ $K_D = 91.2$	0.2
ISE	$K_P = 183.5$ $K_I = 27.35$ $K_D = 68.02$	0.1
$ITSE$	$K_P = 535$ $K_I = 47.5$ $K_D = 90.13$	5.05

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