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ADAPTIVE REGULATION OF THE MANIPULATOR'S MOVEMENT SPEED DEPENDING ON THE DISTANCE TO THE PERSON AND THE LEVEL OF LOAD ON THE ACTUATOR

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ABSTRACT

The article presents an approach to adaptive control of the manipulator speed based on fuzzy logic, which allows taking into account the distance to the person and the level of load on the executive body. The proposed model forms control actions in accordance with the logic of safe human-robot interaction, providing a dynamic change in speed to increase efficiency and safety. The system uses a set of linguistic rules and triangular membership functions to process fuzzy input data. The simulation results demonstrate the stable behavior of the system and confirm the feasibility of using fuzzy approaches in controlling the movement of manipulators in variable conditions. The developed approach has high potential for implementation in robotic systems that operate in close proximity to a person. Development prospects include integration with machine learning and real-time use on embedded platforms.

Keywords: Adaptive Control, Manipulator, Fuzzy Logic, Speed Of Movement, Distance To A Person, Load, Executive Body, Real-Time Control, Robotics, Safe Interaction.

INTRODUCTION

In the modern conditions of industrial development, oriented on the principles of Industry 5.0, intelligent collaborative robotic systems are becoming increasingly important, capable of effectively interacting with a person in a dynamic environment [1]-[14]. Such interaction requires not only high accuracy and reliability of mechanical performance, but also flexibility and adaptability to changes in external conditions, in particular, to the appearance of a person in the working area of the manipulator and to changes in the load on its executive body. Therefore, various methods and approaches can be used here [15]-[34].

One of the key aspects of ensuring safe and effective interaction between a person and a robot is adaptive regulation of the manipulator's speed, which allows minimizing the risks of injury, reducing wear of mechanical components and increasing the energy efficiency of the system [35]-[39]. Traditional control methods do not always provide the necessary level of flexibility in cases where the characteristics of the environment change in real time, therefore there is a need to apply intelligent approaches, such as fuzzy logic (Fuzzy Logic), capable of effectively processing imprecise and linguistically described input data [40]-[43]. The use of fuzzy logic allows us to implement an adaptive control model that takes into account the approximate position of a person relative to the manipulator, the current load on its executive body and other variables that determine the appropriate speed of movement. This approach provides a balance between safety, productivity and adaptability of the system, which is especially important in conditions of variable production processes and the integration of robotic devices into an environment with the presence of a person.

Research in this area is extremely relevant given the need to develop new generation cyber-physical systems that should provide both a high degree of automation and compliance with standards of safe human-machine interaction. In this context, the proposed research topic is aimed at developing a mathematical model of adaptive control that allows regulating the speed of movement of the manipulator based on the assessment of spatial interaction with a person and load characteristics, which significantly increases the level of intellectualization of control in robotic systems.

LITERATURE REVIEW

In the work of H. Jiang, an approach to controlling a manipulator with flexible joints based on a predetermined time is investigated using a composite fuzzy adaptive control with a fully actuator approach of high order, which allows achieving a stable motion trajectory taking into account complex dynamics and uncertainties of the system [44]. This solution provides high control accuracy and fast error decay within a given time.

In the study of H. Shan, a fixed-time self-starting fuzzy adaptive control method for multi-link manipulators is proposed, which allows reducing the frequency of calculations and resource consumption while ensuring accurate trajectory tracking [45]. The proposed method is suitable for systems with limited computational capabilities, but requires accurate parameterization for complex dynamic scenarios.

The article by V. Tinoco presents an overview of modern methods for controlling robotic manipulators, in particular, the importance of integrating adaptive control with fuzzy and neural network approaches to ensure flexible behavior in variable conditions is emphasized [46]. This generalization is useful for forming a general approach in research, but does not provide a specific solution that can be directly applied.

In the work of B. M. Yilmaz, adaptive control based on fuzzy logic for manipulators with BLDC motors is developed, which allows taking into account the characteristics of the drive, ensuring stable control even with dynamic load changes [47]. This approach can be integrated into similar adaptive speed control systems, but is limited only by the type of motor used.

In the study of W. Sun, a hybrid trajectory tracking method based on an improved particle optimization algorithm in combination with a fuzzy PD controller is proposed, which allows achieving high control accuracy under complex external disturbances [48]. This method demonstrates good results in simulations, but requires high computational resources.

In the work of Y. Zhang, adaptive control with state error prediction for flexible manipulators using neural networks with radial basis functions and the dynamic surface control method is considered, which allows adapting to changes in the system structure [49]. The method is effective for nonlinear systems, but requires a long preliminary preparation of the model.

In the article of W. Zhang, control of a predetermined time for manipulators with elastic actuators based on fuzzy logic is investigated, which allows reducing the risk of reaction delay when working in conditions of interaction with a person [50]. This approach is promising for integration into collaborative robotics systems.

In the study of W. Zhao, a method of observing disturbances based on adaptive control with an event trigger is implemented to coordinate the actions of several flexible manipulators, which ensures synchronization of their actions even with partial disturbances [51]. The approach is useful for multi-agent systems, but the excessive level of complexity does not allow it to be easily implemented for a single manipulator.

In the work of P. K. Muthusamy, adaptive neuro-fuzzy control for aeromanipulators is proposed, taking into account the variability of battery power, which ensures stable control under conditions of limited power resources [52]. This approach is important for mobile robotic platforms, although it requires detailed tuning of the system for specific conditions.

In general, the analysis shows the high relevance of research in the field of fuzzy adaptive control of manipulator motion, especially taking into account variable external factors, such as the distance to a person or the load level. The development of models based on Fuzzy Logic allows you to create flexible, safe and effective control systems that can adapt to the real operating conditions of robotic systems, which is especially important for their use in collaborative scenarios in industry and service robotics.

MATHEMATICAL SUPPORT FOR THE MODEL OF THE MANIPULATOR SPEED ADAPTIVE CONTROL BASED ON FUZZY LOGIC

Fuzzy Logic is a mathematical logic method that allows you to work with fuzzy, incomplete or linguistically described data, in contrast to traditional binary logic with a clear division into true or false. It imitates the way of human thinking, allowing systems to make decisions based on approximate concepts such as "close", "fast", "high load". This approach is especially effective in complex, dynamic or insufficiently formalized environments where it is difficult to determine the exact boundaries between states. Fuzzy Logic is widely used in control systems, expert systems and robotics to implement adaptive and intuitive control.

As part of these studies, we conduct the following input system variables: $d \in [0, D_{max}]$ – distance to a person (m); $l \in [0, L_{max}]$ – load level on the manipulator (H); $v \in [v_{min}, v_{max}]$ – manipulator movement speed (system output) (m/s).

The first step is to build Fuzzy sets, which allow formalization of linguistic variables that describe vague or approximate concepts, such as "low speed", "close distance" or "high load". It allows the system to take into account the degree of membership of elements in a set, and not simply assign them the status of truth or falsehood. This provides flexible and adaptive decision-making in complex or changing conditions typical of human-robot interaction environments.

For the input variable distance to a person d the following linguistic changes are proposed.

Near:

$$\mu_{Near}(d) = \begin{cases} 1, & d \le a_1 \\ \dfrac{a_2 - d}{a_2 - a_1}, & a_1 < d < a_2 \\ 0, & d \ge a_2 \end{cases} \tag{1}$$

Medium:

$$\mu_{Medium}(d) = \begin{cases} 1, & d \le a_1 \; or \; d \ge a_3 \\ \dfrac{d - a_1}{a_2 - a_1}, & a_1 < d < a_2 \\ \dfrac{a_3 - d}{a_3 - a_2}, & a_2 \le d < a_3 \end{cases} \tag{2}$$

Far:

$$\mu_{Far}(d) = \begin{cases} 0, & d \le a_2 \\ \dfrac{d - a_2}{a_3 - a_2}, & a_2 < d < a_3 \\ 1, & d \ge a_3 \end{cases} \tag{3}$$

Parameters: a_1 = 0.3m; a_2 = 0.7m; a_3=1.5m.

The following linguistic changes are proposed for the load variable l.

Low:

$$\mu_{Low}(l) = \begin{cases} 1, & l \le b_1 \\ \dfrac{b_2 - l}{b_2 - b_1}, & b_1 < l < b_2 \\ 0, & l \ge b_2 \end{cases} \tag{4}$$

Medium:

$$\mu_{Medium}(l) = \begin{cases} 0, & l \le b_1 \, or \, l \ge b_3 \\ \dfrac{l - b_1}{b_2 - b_1}, & b_1 < d < b_2 \\ \dfrac{b_3 - l}{b_3 - b_2}, & b_2 \le l < b_3 \end{cases} \tag{5}$$

High:

$$\mu_{High}(l) = \begin{cases} 0, & l \le b_2 \\ \dfrac{l - b_2}{b_3 - b_2}, & b_2 < l < b_3 \\ 1, & l \ge b_3 \end{cases} \tag{6}$$

Parameters: b_1 = 0N; b_2 = 30N; b_3 = 60N.
For variable speed output (v) the following linguistic changes are proposed.
Slow:

$$\mu_{Slow}(v) = \begin{cases} 1, & v \le s_1 \\ \dfrac{s_2 - v}{s_2 - s_1}, & s_1 < v < s_2 \\ 0, & v \ge s_2 \end{cases} \tag{7}$$

Moderate:

$$\mu_{Moderate}(v) = \begin{cases} 0, & v \le s_1 \, or \, v \ge s_3 \\ \dfrac{v - s_1}{s_2 - s_1}, & s_1 < v < s_2 \\ \dfrac{s_3 - v}{s_3 - s_2}, & s_2 \le v < s_3 \end{cases} \tag{8}$$

Fast:

$$\mu_{Fast}(v) = \begin{cases} 0, & v \le s_2 \\ \dfrac{v - s_2}{s_3 - s_2}, & s_2 < v < s_3 \\ 1, & v \ge s_3 \end{cases} \tag{9}$$

Parameters: s_1 = 0.05 m/s; s_2 = 0.15 m/s; s_3 = 0.3 m/s.
Lat us develop Fuzzy Rules for this study, and present them in Table 1.
Example of Fuzzy Rules record implementation:

$$\begin{gathered} R1: IF\ d\ is\ Near\ AND\ l\ is\ High\ THEN\ v\ is\ Slow \\ R2: IF\ d\ is\ Medium\ AND\ l\ is\ Medium\ THEN\ v\ is\ Moderate \\ R3: IF\ d\ is\ Far\ AND\ l\ is\ Low\ THEN\ v\ is\ Fast \end{gathered} \tag{10}$$

The next step is defuzzification, these are the final stages in Fuzzy Logic systems, necessary to transform a fuzzy conclusion into a specific, numerical solution that can be applied in real control, in this case, the speed of the manipulator (v^*). To get the final value v^* centroid method is used:

$$v^* = \frac{\int v \cdot \mu_{agg}(v)dv}{\int \mu_{agg}(v)dv} \tag{11}$$

v^* – це the final (defuzzified) value of the output variable, which we obtain as a result of the operation of the fuzzy system (for example, manipulator’s movement speed);

v – is a variable that runs through all possible values of the output variable (e.g., from 0 to maximum speed);

$\mu_{agg}(v)$ – aggregated membership function, which reflects how well each value v fits according to all applied fuzzy rules. It is the result of combining (aggregating) all individual output membership functions after fuzzy inference;

$\int v \cdot \mu_{agg}(v)dv$ – means the "weighted sum" of all possible values of the output variable according to their degree of membership;

$\int \mu_{agg}(v)dv$ – is the total area under the aggregated membership function, which provides the normalization of the result.

Table 1: Fuzzy Rules for the adaptive regulation system of manipulator’s movement speed depending on the distance to the person and the level of load on the executive body.

№	Distance to the person (d)	Load level (l)	Manipulator movement speed (v)
1	Near	Low	Slow
2	Near	Medium	Very slow
3	Near	High	Minimal
4	Medium	Low	Moderate
5	Medium	Medium	Slow
6	Medium	High	Very slow
7	Far	Low	Fast
8	Far	Medium	Moderate
9	Far	High	Slow

*the output variable is manipulator’s movement speed

Expression 11, makes it possible to calculate a single-digit numerical value based on fuzzy inferences obtained from a set of fuzzy rules. Without defuzzification, the system would not be able to transmit a clear value to the actuator, as a controller of the manipulator speed.

Based on the proposed models, the general function of the fuzzy logical inference process for adaptive control of the manipulator speed depending on the distance to the person (d) and the burden on the executive body (l) is next:

$$v^* = Defuzz\left(\bigcup_{i=1}^{N} \min\left(\mu_{A_i}(d), \mu_{B_i}(l) \cdot \mu_{C_i}(v)\right)\right) \tag{12}$$

v^* – is the final value of the manipulator's movement velocity obtained after defuzzification. It is used for adaptive control of the real manipulator in the current environment.;

$Defuzz(\cdot)$ – defuzzification operator that converts an aggregated (combined) fuzzy set into a clear velocity value;

$\min\left(\mu_{A_i}(d), \mu_{B_i}(l) \cdot \mu_{C_i}(v)\right)$ – implements the fuzzy inference rule, where the minimum is selected among the degrees of membership of the input variables (distance d and load l) and output (speed v);

$\mu_{A_i}(d)$ – a membership function that reflects how much the current distance value d (between the manipulator and the human) belongs to the fuzzy set A_i (for example, "near", "medium", "far");

$\mu_{B_i}(l)$ – membership function that determines the degree of membership of the load l to the fuzzy set B_i (for example, "low", "medium", "high");

$\mu_{C_i}(v)$ – membership function for the output variable v, i.e. the speed of movement, which reflects the control rules (e.g., "slow", "moderate", "fast")

Function (12) implements the decision-making logic for the adaptive system: it takes into account how close the person is to the manipulator (for safety), and how loaded the executive body is (to avoid overload). The final speed is chosen based on a comprehensive evaluation of these parameters through a set of fuzzy rules.

DEVELOPMENT OF A PROGRAM FOR ADAPTIVE CONTROL OF THE MANIPULATOR SPEED BASED ON FUZZY LOGIC

The choice of the Python programming language for developing a program for adaptive control of the manipulator speed based on Fuzzy Logic is due to its high flexibility, code readability, a wide range of scientific libraries and support for fuzzy logic through the scikit-fuzzy library. Python allows you to quickly create prototypes and integrate mathematical models with visualization, which is critically important at the research and analysis stage [53]-[56]. The PyCharm 2022.2.3 development environment was chosen due to its stable operation, powerful code autocompletion tools, convenient integration with virtual environments and libraries, as well as the ability to customize the environment to the needs of the project. This provides comfortable development, debugging and visualization of models with a high level of code quality control.

Let us describe a fragment of the software implementation of adaptive control of the manipulator speed based on Fuzzy Logic:

```
# Input variables
distance = ctrl.Antecedent(np.arange(0, 201, 1), 'distance')
load = ctrl.Antecedent(np.arange(0, 101, 1), 'load')
speed = ctrl.Consequent(np.arange(0, 101, 1), 'speed')
```

The code fragment creates three fuzzy variables for the control system: the distance to the person (distance), the load level on the manipulator (load), and the desired speed of movement (speed). The variables distance and load are input (antecedent), and speed is the output (consequent), which is determined based on fuzzy rules. Each variable is defined on its range of values with a step of one for further formation of fuzzy sets.

```
# Fuzzy sets
distance['near'] = fuzz.trimf(distance.universe, [0, 0, 50])
distance['medium'] = fuzz.trimf(distance.universe, [30, 100, 170])
distance['far'] = fuzz.trimf(distance.universe, [150, 200, 200])
load['low'] = fuzz.trimf(load.universe, [0, 0, 30])
load['medium'] = fuzz.trimf(load.universe, [20, 50, 80])
load['high'] = fuzz.trimf(load.universe, [70, 100, 100])
speed['slow'] = fuzz.trimf(speed.universe, [0, 0, 40])
speed['normal'] = fuzz.trimf(speed.universe, [30, 50, 70])
speed['fast'] = fuzz.trimf(speed.universe, [60, 100, 100])
```

This code snippet defines fuzzy sets for each of the system variables - distance, load, and speed - using triangular membership functions. For each variable, three linguistic terms are given: for example, for distance, these are 'near', 'medium', and 'far', each of which is described by a certain interval of values. This forms a fuzzy knowledge base that allows the system to make decisions based on fuzzy logic.

```
# Rules
rules = [
```

```
    ctrl.Rule(distance['near'] & load['high'], speed['slow']),
    ctrl.Rule(distance['near'] & load['medium'], speed['slow']),
    ctrl.Rule(distance['near'] & load['low'], speed['slow']),
    ctrl.Rule(distance['medium'] & load['high'], speed['slow']),
    ctrl.Rule(distance['medium'] & load['medium'], speed['normal']),
    ctrl.Rule(distance['medium'] & load['low'], speed['normal']),
    ctrl.Rule(distance['far'] & load['high'], speed['normal']),
    ctrl.Rule(distance['far'] & load['medium'], speed['fast']),
    ctrl.Rule(distance['far'] & load['low'], speed['fast'])
```

This code snippet creates a set of fuzzy rules for a decision-making system that determine how fast the manipulator should move, depending on a combination of distance to the person and load level. Each rule is formulated as a logical statement of the type "if... then...", where, for example, at a short distance and a high load, the speed will be low. Such rules are the basis for deriving a decision in a fuzzy logic system.

```
# System construction
speed_ctrl = ctrl.ControlSystem(rules)
speed_sim = ctrl.ControlSystemSimulation(speed_ctrl)
```

The code snippet creates a control system based on the given fuzzy rules and initializes a simulation object for further calculation of the results. speed_ctrl combines all the rules into a single fuzzy system, and speed_sim allows you to perform simulations, calculating the output speed values based on the input data on distance and load.

```
# Simulation of values
distance_vals = np.arange(0, 201, 5)
load_vals = np.arange(0, 101, 5)
X, Y = np.meshgrid(distance_vals, load_vals)
Z = np.zeros_like(X)
for i in range(len(distance_vals)):
    for j in range(len(load_vals)):
        speed_sim.input['distance'] = X[j, i]
        speed_sim.input['load'] = Y[j, i]
        speed_sim.compute()
        Z[j, i] = speed_sim.output['speed']
```

The code fragment performs simulation of the adaptive speed of the manipulator for all combinations of distance and load values. Using the grid of distance_vals and load_vals values, it forms matrices X and Y, which represent the space of input parameters. In the loop, each pair of values is fed to the input of the fuzzy control system, the calculation is performed, and the corresponding speed value is written to the matrix Z for further visualization.

Let's simulate the adaptive speed control of the manipulator based on Fuzzy Logic, with the following parameters: d= from 0 to 200 with a step of 5 cm; l = from 0 to 100% with a step of 5%. The simulation results are presented in Figure 1.

The obtained graph of adaptive control of the manipulator speed based on fuzzy logic demonstrates the interdependence between the distance to the person and the level of load on the executive body in the context of changing the speed of the manipulator movement. The X axis displays the change in the distance to the person from 0 to 200 cm, the Y axis - the load level from 0 to 100%, and the Z axis - the calculated speed of the executive body in the range from 0 to 100% in the relative scale.

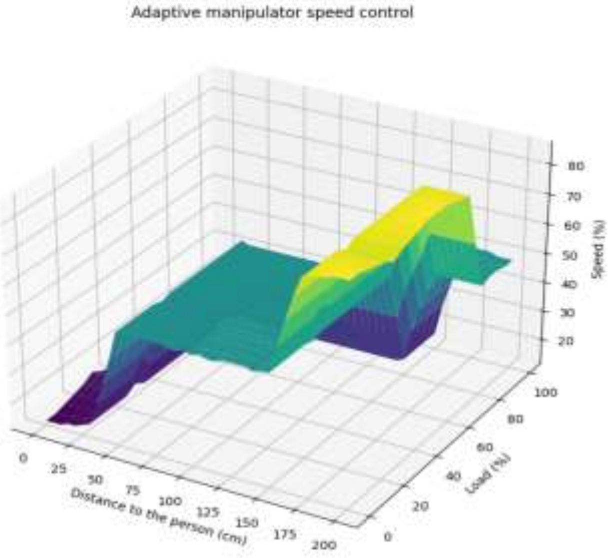

Figure 1: Graph of adaptive control of the manipulator speed with the following parameters: *d* = from 0 to 200 in 5 cm increments; *l* = from 0 to 100% in 5% increments.

Analysis of the graph shows that at a small distance to the person, regardless of the load level, the system makes a decision to reduce the manipulator speed to minimum values. This is justified by safety criteria in conditions of work with a person, which meets the requirements for collaborative robots. In the medium distance zone, approximately from 50 to 130 cm, the speed gradually increases depending on the load level - at high load it remains lower, which indicates a limitation of the dynamics of movement to avoid inertial overloads and possible collisions, while at low load the speed can reach medium values. In the long distance range, over 150 cm, the speed reaches the maximum permissible values, especially at low load, which ensures effective system performance in the absence of risk for the operator. The presence of characteristic “steps” or plateaus on the surface of the graph is associated with the discretization of input values and the method of defuzzification in the fuzzy system. It is also seen that at maximum load even at a long distance the system does not allow to reach peak speeds, which indicates a limitation for reasons of stability and reliability. Thus, the results of graphical modeling confirm the effectiveness of using fuzzy logic for adaptive speed control, ensuring a balance between safety, load and performance in collaborative robot motion control systems. The constructed model demonstrates a clear zonal adaptation of the executive body's behavior to the external environment and current state, which is an important step towards the implementation of flexible and safe robotic systems of the new generation.

CONCLUSION

As a result of the research, a model of adaptive control of the manipulator speed based on fuzzy logic was developed and implemented, which allows for effective consideration of the distance to the person and the level of load on the executive body. The developed control system provides flexible control of the dynamics of the manipulator movement, increasing the safety of joint work between a person and a robot. The model demonstrated high adaptability to changes in external conditions and the ability to make logical control decisions even with fuzzy or contradictory input data. The modeling results confirm that when the distance to the person decreases, the system automatically reduces the speed, which meets the requirements of safe operation in conditions of human-machine interaction. In cases of reduced load and increased distance, the system allows for an increase in speed, which ensures increased efficiency in performing production tasks. The constructed model can be easily scaled and adapted to other types of manipulators and usage scenarios. The use of fuzzy logic allowed for the formalization of fuzzy expert knowledge in the form of a set of simple rules, which greatly simplifies further modification of the system. This approach is promising for integration into control systems for collaborative robots, autonomous manipulators, and service robots. The results obtained can be used as a basis for creating intelligent safety modules in human-robotic environments. Further research should be directed at combining fuzzy logic with machine learning methods for automatic generation and optimization of rules. Another promising direction is the implementation of the developed model on embedded platforms with real feedback from load and distance sensors. It is possible to expand the control system to multidimensional tasks, taking into account the speed of a person's approach, the type of task being performed, or the load configuration. In the future, combined approaches that combine fuzzy control with predictive or adaptive control can be explored. The results of this study open up opportunities for integrating fuzzy logic into new-generation robotic systems that must operate in conditions of uncertainty and a changing environment.

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