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Design of Telemedicine Robot using Behavior-based Control Architecture with Two-Step Fuzzy Logic Optimization

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Abstract: Designing a telemedicine robot is a challenging task. Complexity, incomplete prior knowledge of the environment and unexpected situations set strict requirements for both the hardware and software components of the robot. Several robotics architectures have been proposed that try to cope with the above problems. The behavior-based approach has been established as the main alternative to new robot control. The paper presents the design and prototype of a telemedicine robot using behavior-based control architecture. Several behaviors will design to assist the robot, such as: Remotely control, seeing the situation and detecting obstacles when the robot maneuvers. A fuzzy behavior-based used in one of the behaviors. A Two-Step Fuzzy Optimization is used to optimize the fuzzy parameters and generate a robust and smooth braking system. Based on several experiments, the robot can maneuver properly as instructed. In general, it can be said that the design of telemedicine robots works with excellent performance.

Keywords: Telemedicine Robot, Behavior-Based, Fuzzy Logic, Two-Step Fuzzy Optimization

Introduction

Over the past decade, robots have gained wide acceptance for working in the medical field and hospitals to increase the safety and automation of health care. It is expected that they will soon be an essential part of hospitals performing a variety of tasks. One of using a robot in the medical field is a telemedicine robot. Telemedicine robot is a mobile robot that has been used for transporting material of medical or assisted a doctor in a place is hazardous to human, or are inaccessible or distant and remotely controlled the robot via any telecommunication media. Some examples of telerobotic are laparoscopic surgery being done with the help of a telerobot, or doctors using remotely located robots to communicate with their patients, which enables them to treat patients anywhere in the world (Huang *et al*., 2019; Koceska *et al*., 2019).

However, designing a telemedicine robot is a challenging task. Complexity, incomplete prior knowledge of the environment and unexpected situations set strict requirements for both the hardware and software components of the robot. The robot should have the ability to perceive and to handle inaccurate and imprecise sensors. The robot also needs to achieve high levels and complex goals with imperfect actuators at a limited time and fast response (Dallal *et al*., 2012; Arent *et al*., 2012; Mariappan *et al*., 2011). An architectural framework for sensing and reasoning process must provide a structure to overcome these problems.

The control architecture of a robot is the backbone of a complete robot system. Several robotics architectures have been proposed that try to cope with the above problems (Tzafestas, 2018; Priyandoko *et al*., 2018). Most of the architectural style described in the technical literature can be classified into four categories: Deliberative control architecture, reactive control architecture, hybrid control architecture and behavior-based control architecture (Munoz *et al*., 2019; Freire *et al*., 2018; Pandey and Parhi, 2016). Unfortunately, designing a reactive control architecture is not easy and requires a slow calculation process that causes inaccurate control actions. While integrating reactive control architecture with behavior-based control architecture in the form of hybrid control architecture produces a system that is not simple and complex, causing control actions that are not reliable. Therefore, the behavior-based approach has been

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established as the main alternative to conventional robot control. Behavior-based architectures are bottom-up approaches inspired by biology and consist of decomposing the problem of autonomous control by task rather than by function.

On the other hand, some control techniques have been provided to obtain robust behavior. This control technique is needed to generate a properly controlled manner that relates the perception and action of behavior. Therefore, several works including simple if-then logic and conventional control up to intelligent control, such as Fuzzy Logic, Neural Network, Genetic Algorithm and Evolutionary Programming have been proposed. Fuzzy logic is among the most common technique for behaviors. Fuzzy logic is approximate reasoning that can cope with uncertainty in information so that it can overcome behavior-based problems. The combination of fuzzy control and behavior-based architecture has some further advantages. In this case, fuzzy control is used in the domain of autonomous robotics to implement individual behavior units and stated as Fuzzy Behavior-based (Mohanta and Keshari, 2019; Hacene and Mendil, 2019; Gyawali and Agarwal, 2018; Faisal *et al*., 2013).

The contribution of this paper is a design process for a telemedicine robot using a behavior-based control architecture. One of the behaviors is controlled using fuzzy logic. The fuzzy parameters are optimized with two-faces optimization. The main function of this robot is to handle and transport several materials within the hospital to reduce risks in the hazardous zone. Several behaviors will design to assist the robot, such as: remotely control, seeing the situation and obstacles avoidance. Behavior coordination is designed using competitive coordination, especially for obstacle avoidance behavior. Several experiments have been done. The paper is closed with some conclusion.

Method

Behavior-based Control Architecture

In classical robotic, control architecture is serial processing units where the architecture works through a cycle of Sense-Plan-Action as depicted in Fig. 1. On the other hand, behavior-based control architecture is a biologically inspired, distributed, bottom-up approach and consists of decomposing the problem of autonomous control by task rather than by function. In this control architecture, the robot task is decomposed into several modules, called behaviors as shown in Fig. 2. A behavior is a direct mapping of sensory inputs to a pattern of motor actions that are then used to achieve a task (stimulus-response), so each behavior has full access to all robot sensors and processes its command to drive the robot actuators.

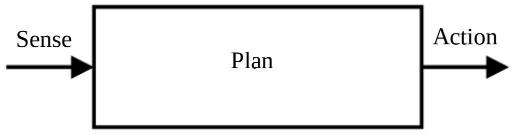

Fig. 1: Sense-plan-action control architecture

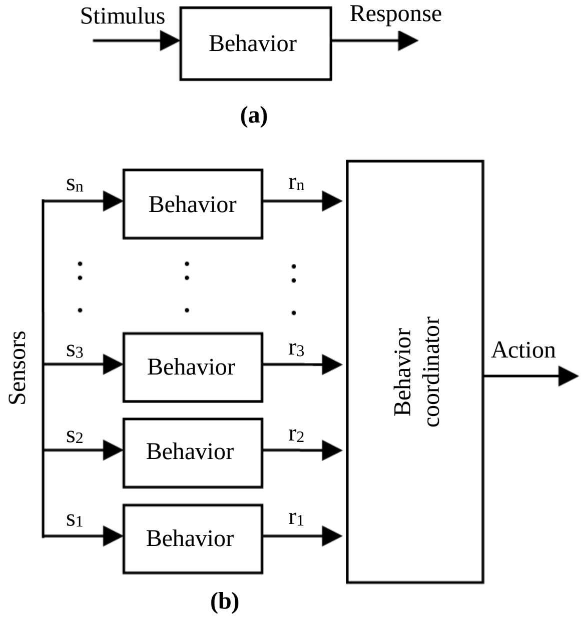

Fig. 2: Behavior-based Control Architecture: (a) Individual Behavior (b) Complete Block Diagram

The parallel structure of simple behaviors allows a real-time response with a low computational cost. Basic behaviors could be "target tracking," "obstacle avoiding," "wall following," and so on. Behaviors with different objectives may produce conflicting actions; therefore, behavior coordination is needed to select the action that satisfies the system objective. Behavior coordination can be cooperative or competitive. In cooperative coordination (behavior fusion), the behaviors are combined with a set of weights, each behavior can have the opportunity to contribute to the control output; while in competitive coordination (behavior arbitration), the behaviors compete to win the control of the robot, only one behavior's output will be valid at any time.

Formally, a behavior can be expressed as (S, R, β), where:

S: Stimulus Domain. S is the domain of all perceivable stimuli. Each behavior has a stimulus domain.

R: Range of Response. For autonomous vehicles with six degrees of freedom, the response $r \in R$ of behavior is six-dimensional vector: $r = [x, y, z, \varphi, \theta, \psi]$ composed of the three translation degrees of freedom and the three rotational degrees of freedom. Each parameter is composed of strength and orientation values. When there are different responses r_i, the final response is $r_i' = g_i.r_i$, where g_i is gain, which specifies the strength of the behavior relative to the others.

β: Behavioral Mapping. The mapping function "β" relates the stimulus domain with the response range for each active behavior:

$$\beta(S) \rightarrow R \tag{1}$$

where behavioral mappings, β, can be discrete or continuous.

Robot Model

Figure 3 shows a model of a mobile robot for simulation exercises and investigating the performance of the algorithm. The mobile robot is located on a two-dimensional Cartesian workspace, in which a global coordinate $\{X,O,Y\}$ is defined. The robot has three degrees of parameter position that are represented by a posture $p_c = (x_c, y_c, \theta_c)$, where (x_c, y_c) indicates the spatial position of the robot guide point in the global coordinate system and θ_c is the heading angle of the robot counter-clockwise from the x-axis.

The mathematical model for the robot movement can be obtained with a differentially steered drive system (Adriansyah and Amin, 2008) or also known as a differential drive system (Adriansyah and Amin, 2008). The system is commonly used in small mobile robots because of some advantageous, which are simple, reliable and familiar from ordinary life. The system is based on two wheels mounted on a single axis, which are independently powered and controlled that provide both drive and steering functions. While the velocity of each wheel varies the robot must rotate about a point that lies along their common left and right wheel axis. The point that the robot rotates about is known as the Instantaneous Center of Curvature (ICC), as depicted in Fig. 4.

By varying the velocities of the two wheels, the trajectory that the robot takes will vary, as well. Since the rate of rotation ω_c about the ICC must be the same for both wheels, it can be written as follows:

$$\omega_c\left(R+\frac{W}{2}\right)=v_r \tag{2}$$

$$\omega_c\left(R-\frac{W}{2}\right)=v_l \tag{3}$$

where, R is the signed distance from the ICC to the midpoint between the wheels, W is the distance between the center of the two wheels, ω_c is the angular velocity of the robot and v_r and v_l are the right and the left wheel velocities along the ground, respectively.

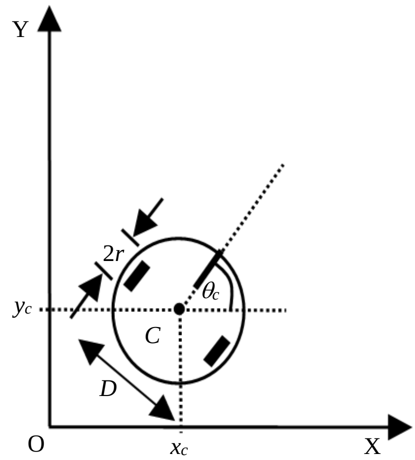

Fig. 3: Model of mobile robot

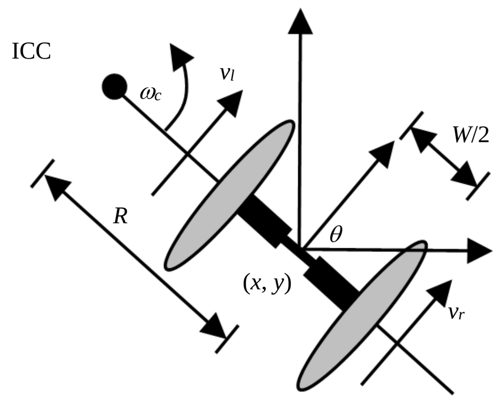

Fig. 4: Differentially steered drive systems

At any instance, in time, Equation (4.1) and Equation (4.2) can be solved for R and ω_c as:

$$R=\frac{W}{2}\left(\frac{v_r+v_l}{v_r-v_l}\right) \tag{4}$$

$$\omega_c=\left(\frac{v_r-v_l}{W}\right) \tag{5}$$

and:

$$v_c=\left(\frac{v_r+v_l}{2}\right) \tag{6}$$

where, v_c is the linear velocity of the robot found as the average of the two wheels.

There are three interesting cases with these kinds of drives based on Equations (4.3) to (4.5):

1. If $v_l = v_r$, then the robot moves in a straight line with v_c. R becomes infinitive and there is effectively no rotation because ω_c is zero
2. If $v_l = - v_r$, the R is zero and the robot pivots at the midpoint of the wheel axis
3. If v_r is equal to zero, the robot rotates about the left wheel and $R = W/2$. The reverse is true if v_l is equal to zero

Based on these combinations, the robot can move to different positions and orientations as a function of time. The derivatives of x, y and θ can be obtained as:

$$\frac{dx}{dt} = v_c \cos\theta_c \tag{7}$$

$$\frac{dy}{dt} = v_c \sin\theta_c \tag{8}$$

$$\frac{d\theta}{dt} = \omega_c \tag{9}$$

By applying the current position of the robot, $p_c = (x_c, y_c, \theta_c)$, the next current position of the robot, $p_{c+1} = (x_{c+1}, y_{c+1}, \theta_{c+1})$, in simple form is:

$$x_{c+1} = x_c + v_c \cos\theta_c \tag{10}$$

$$y_{c+1} = y_c + v_c \sin\theta_c \tag{11}$$

$$\theta_{c+1} = \theta_c + \omega_c \qquad (11)$$

Fuzzy Behavior-based Design

The combination of fuzzy control and behavior-based architecture has some further advantages. It can produce controllers that are robust to uncertainty and imprecision based on a set of IF-THEN rules in which the expert knowledge can be employed. The big centralized controller is reduced to distributed smaller sub-controllers. Fuzzy behavior-based control architecture consists of a set of horizontally organized, distributed, independent fuzzy behaviors and a system of behavior coordination. Each behavior is a fuzzy logic control system that responds to its stimuli by issuing a single command that is transmitted for command coordination. Priority-Based behavior coordination is used in this paper. A priority-based mechanism action is selected by a central module based on a priori assigned priorities. Thus, behaviors with higher priorities are allowed to take control of the robot.

Figure 5 provides an architectural overview of a behavior-based mobile robot proposed in this work based on Two-Step Fuzzy Optimization. The control architecture is decomposed into three blocks, which are as Sensors Block, Behaviors Block, Behaviors Coordination Block and Two-Step Fuzzy Optimization Block. There are three sensor-behavior pairs, camera control behavior, robot control behavior and fuzzy obstacle avoidance behavior. The fuzzy obstacle avoids behavior is set to be a priority behavior.

Camera control behavior is a behavior that is used to control the position of the camera. A series of pushbuttons will be designed to determine the desired camera position.

The position of the camera determines the scope of the medical team's view of the patient's condition and the environment around the patient.

Whereas robot control behavior is the behavior that determines the movement of the robot. The robot movement used the principle that has been described in advance. Some robot movements are determined by the pushbutton position that is designed. Some robot movements that can be controlled are forward, backward, turn right and left turn left motion, respectively. Both of these behaviors are controlled wirelessly.

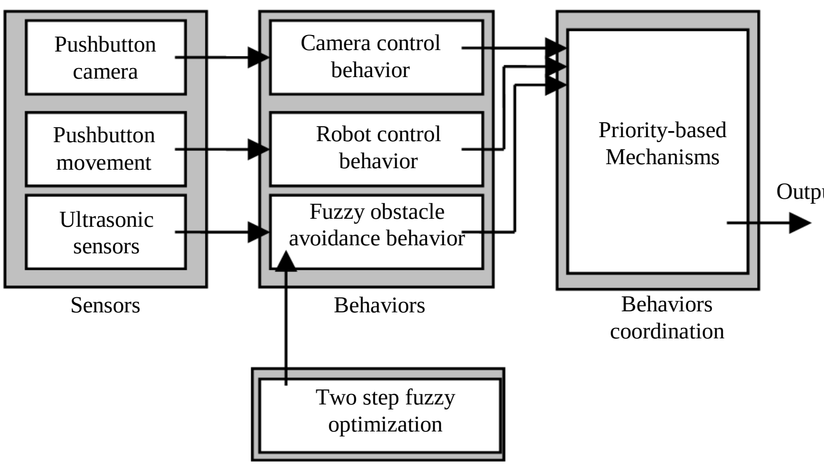

Fig. 5: Control architecture of the proposed design

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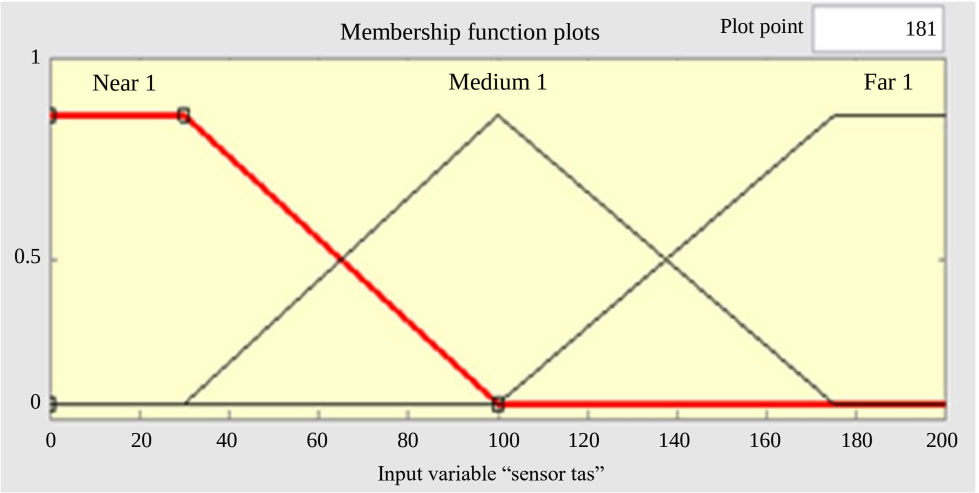

Fig. 6: Membership function for inputs Variables

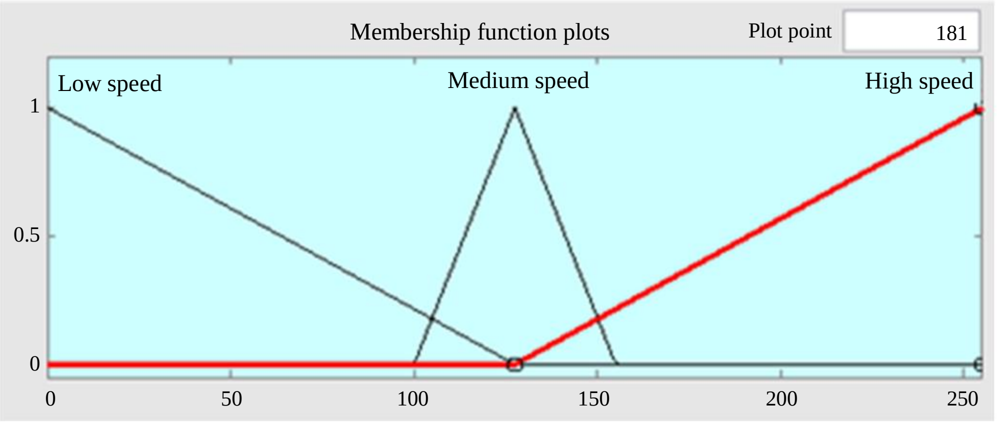

Fig. 7: Membership function for PWM Output Variable

Finally, fuzzy obstacle avoidance behavior is behavior that can avoid obstacles by braking automatically. The braking process uses the Fuzzy Logic principle. Input variables can be obtained from three SRF04 ultrasonic sensors arranged vertically to detect obstacles in front of the robot. The top sensor is installed at the top of the pole, the center sensor is at the center of the pole and the bottom sensor is at the bottom of the pole. While the output for the fuzzy logic is the PWM value for the right wheel speed and left wheel speed. A set of fuzzy inferences has been designed to generate suitable action. Fuzzy membership function for inputs and output is shown in Fig. 6 and 7, respectively.

Performance of a control system that using fuzzy logic is determined by a fuzzy logic membership function. In several cases, a triangular function is most preferred because of the easy in the design process (Adriansyah and Amin, 2008; Monicka *et al*., 2010). The value of the center and base width of a triangular give a significant effect of control performance. Therefore, to get the best performance control, the value of a center and base width of a triangle function must have an optimal value.

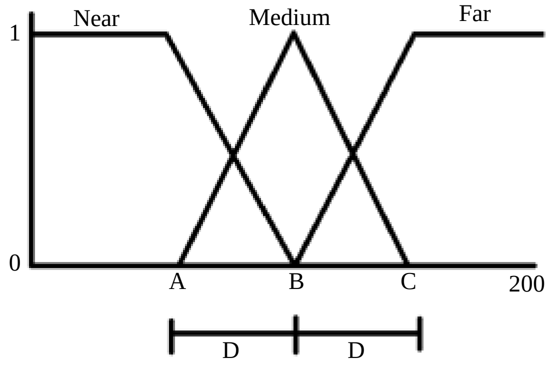

Fig. 8: Two-steps fuzzy optimization

The optimization process takes place in two stages, that is called Two Steps Fuzzy Optimization. The first step is finding the value of the center of each variable of the membership function used, which are A, B and C, respectively. The search is done by shifting some value iteratively. Then, in the second stage is the search for

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value for the base width of each variable of the membership function used, D. As the previous stage, the search is carried out by shifting some value as well. The principle of optimizing the membership function value is shown in Fig. 8.

The designed behaviors are part of the overall telemedicine robot functions. Thus, the robot is expected to move automatically or controlled by the operator, taking data around the patient through the camera and can avoid obstacles in front of him. Thus, the medical process between doctors and patients can be done remotely via the Graphic User Interface (GUI) using the internet network.

Result and Discussion

The prototype is made using a square plywood board and the stake uses aluminum, as shown in Fig. 9. The size robot is 40 cm wide, 60 cm in length and 100 cm in high. On the back of the robot, there is a switch to turn on and turn off the robot, besides there is also a charger port to recharge the robot battery that runs out. For its resources, this robot uses a lithium-ion battery with 22 volts.

The GUI, as shown in Fig. 10, has been designed to camera control behavior and robot control behavior. The behavior will take several actions based on the key pressed. Another GUI displays the camera capture results in real-time, as shown in Fig. 11. All communication between the GUI and the robot is through wireless communication using the internet.

Two Steps Fuzzy Optimization testing is done in 2 steps for fuzzy obstacle avoidance behavior. In the first stage, the search results are shown in Fig. 12. Figure 12 shows the relationship between the movement of the robot to do automatic braking based on the price of the midpoint of each membership function. An RMS analysis is performed to get the best results, as shown in Table 1. to make sure that the movement is robust and smooth.

Based on Table 1, the best price determined for the midpoint of each membership function is 403.24. This first step optimization result is A = 60, B = 110 and C = 160.

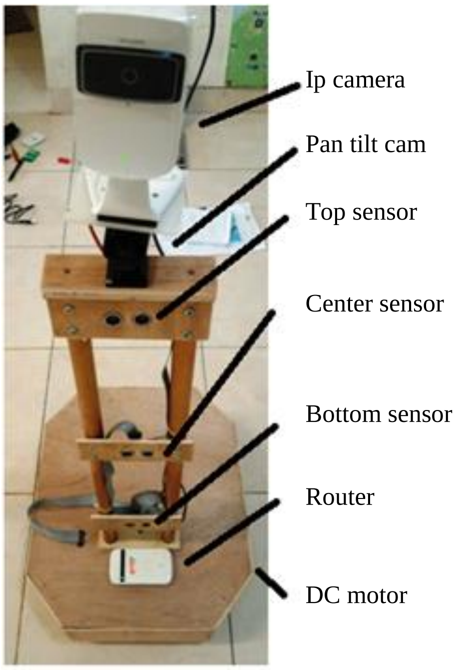

Fig. 9: Telemedicine robot prototype

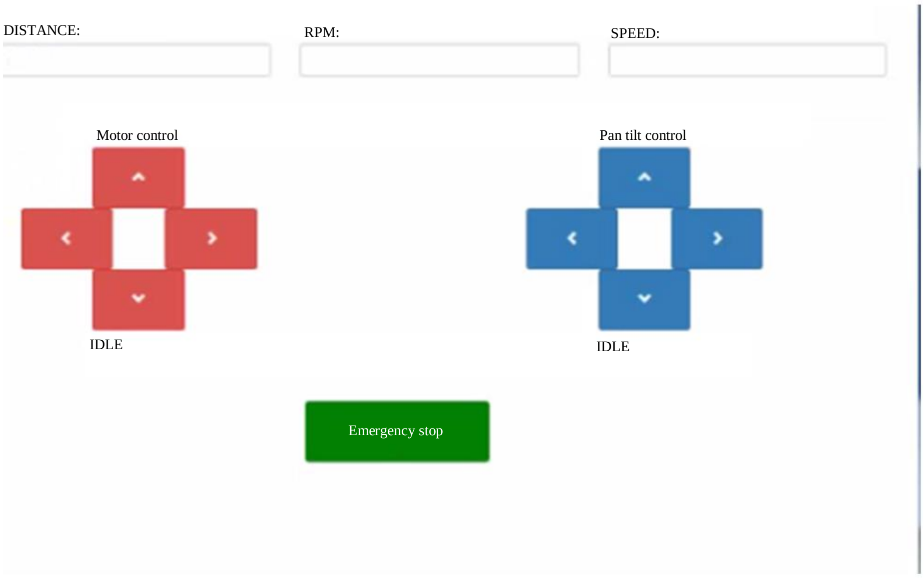

Fig. 10: Telemedicine robot prototype

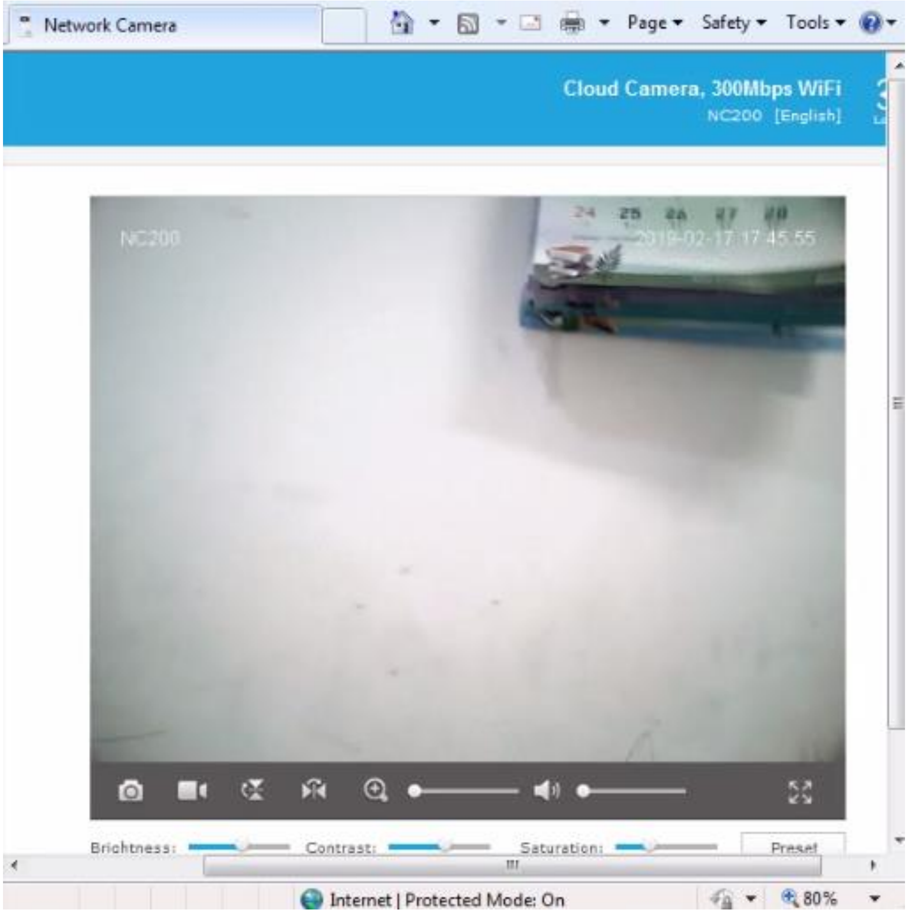

Fig. 11: Telemedicine robot prototype

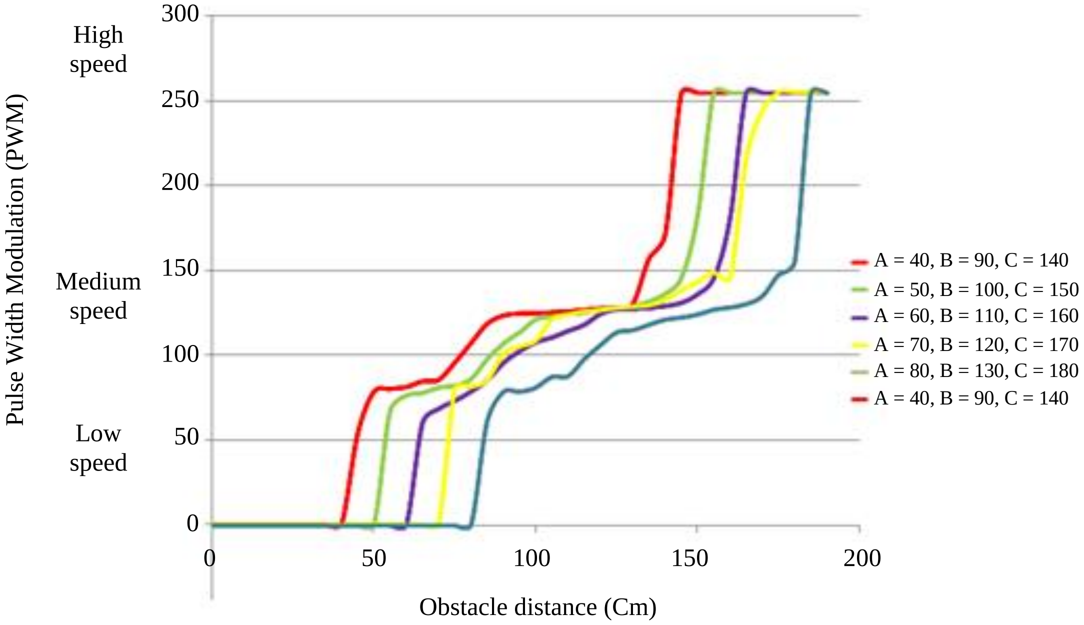

Fig. 12: Result of the first step of fuzzy optimization

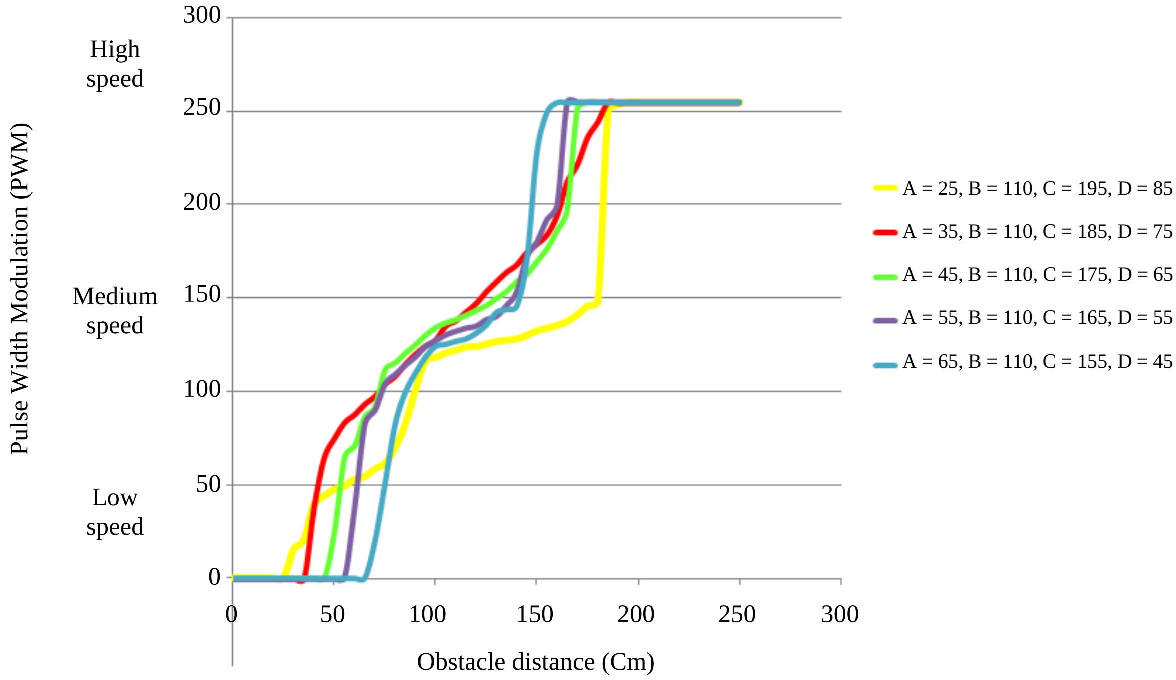

Fig. 13: Result of the second step of fuzzy optimization

Table 1: RMS analysis of first step of fuzzy optimization

No.	Δx^2 (A = 40, B = 90 and C = 140)	Δx^2 (A = 50, B = 100 and C = 150)	Δx^2 (A = 60, B = 110 and C = 160)	Δx^2 (A = 70, B = 120 and C = 170)	Δx^2 (A = 80, B = 130 and C = 180)
1	6953.89	5249.00	5498.22	118.15	9890.30
2	203.3476	1332.25	1232.01	798.6276	59.29
3	720.9225	88.7364	90.25	4939.2784	159.7696
4	5.5696	20.5209	24.7009	11.0224	21.9961
5	0.09	7.5625	3.8025	32.6041	4
6	0.9604	0.7744	1.3924	23.8144	1.5625
7	0.7396	0.3721	0.2704	32.0356	8.4681
8	0.25	5.4289	0.0169	10.6276	2.9929
9	0.25	0.7744	7.9524	0.5476	1.4884
10	0.0625	1.7424	40.7044	0.6241	9.3025
11	1.5129	3.7249	12.8164	1.9044	10.49
12	23.5225	57.1536	15.2881	0.3364	1.6384
13	130.1881	42.25	7.7841	3.5344	56.25
14	131.3316	85.0084	28.3024	8.41	67.56
15	103.6324	137.5929	47.4721	159.0121	101.80
16	0.7921	14.1376	103.6324	11.0224	0.1681
17	11.56	1.7956	45.1584	18.7489	40.06
18	1.1664	9.61	29.48	243.36	6.0025
19	3.0625	2.2801	22.65	14.21	0.0256
20	603.68	83.90	67.40	2.01	294.46
21	2823.85	4475.61	3608.40	6245.7	3728.32
22	0.6241	0.3844	0.1936	1.1025	0.2116
$\sum\Delta x^2/n$	**444.83**	**505.24**	**403.25**	**422.56**	**413.32**

Then, the same process is done to determine the width of the membership function. The results of searching for the membership function width are shown in Fig. 13 and the RSM calculation results are corrected in Table 2.

Based on Table 2, the best price determined for the midpoint of each membership function is 126.704. This second step optimization result is D = 75, then A = 35, B = 110 and C = 75. Therefore, based on this parameter, the obstacle avoidance behavior is performed.

Table 2: RMS analysis of second step of fuzzy optimization

No.	Δx^2 (A = 65, B =110 C = 155 D = 45)	Δx^2 (A = 65, B = 110 C = 155 D = 45)	Δx^2 (A = 45, B = 110 C = 175 D = 65)	Δx^2 (A = 35, B=110 C = 185 D = 75)	Δx^2 (A = 25, B = 110 C = 195 D = 85)
1	25	3025	12.8164	107.7444	1.5876
2	466.128	59.136	2904.132	68.89	13.1044
3	3374.448	148.596	128.368	209.670	10322.56
4	597.3136	63.6804	95.0625	85.0084	7.0225
5	3.0976	354.1924	46.6489	319.3369	21.5296
6	2.2201	49.7025	45.9684	108.16	12.8164
7	46.7856	33.8724	16.6464	24.3049	4.8841
8	18.8356	3.3489	26.01	20.7025	2.2201
9	9.2416	11.56	14.44	44.7561	1.9881
10	1.6384	1.2321	14.6689	14.8996	5.8564
11	2.4964	2.5921	6.9696	27.1441	4
12	1.1664	3.9204	6.6049	27.6676	0.49
13	32.8329	9.1809	5.4289	39.69	0.4489
14	73.96	10.0489	2.7889	20.9764	2.0449
15	107.744	30.580	6.7081	21.9024	1.44
16	286.624	19.624	16.4025	7.5625	0.0729
17	1019.524	24.601	26.4196	57.6081	2.9241
18	947.408	25.401	20.25	9.6721	2.2201
19	396.80	202.777	27.2484	20.0704	5.76
20	0.04	52.128	13.69	28.1961	4.2849
21		1961.604	398.800	42.1201	242.4249
22		1430.352	26.7289	18.49	335.2561
23		0.6241	247.1184	41.4736	160.0225
24			35.4025	17.7241	68.89
25			1600	31.2481	8.5264
26			609.596	18.49	17.64
27			0.0144	71.0649	1.7161
28				106.502	14.44
29				685.392	2.6244
30				1504.664	13.4689
31					20.9764
32					358.7236
33					24.7009
34					231.6484
35					0.0144
$\sum\Delta x^2/n$	**370.66**	**327.119**	**235.367**	**126.704**	**340.523**

Overall, the results of this experiment are following suggested research delivered by Huang *et al*. (2019) that a good control architecture produces a reliable telemedicine robot system. Besides, the proposed robot maneuverability is similar to the design of Koceska *et al*. (2019) where the robot can avoid obstacles optimally to the planned target point.

Conclusion

A prototype telemedicine robot has been designed. The design of telemedicine robots uses behavior-based control architecture. Several behaviors have been designed, such as camera control behavior, robot movement behavior and obstacle avoidance behavior. The designed behaviors are part of the overall telemedicine robot functions. Behavior coordination uses a priority-based mechanism to ensure that collisions do not occur. For obstacle avoidance behavior designed using fuzzy behavior whose parameters are optimized using Two-Step Fuzzy Optimization.

In general, telemedicine as a result of design can work well. The robot can maneuver properly as instructed. The camera capture results can also be done perfectly. Both of these behaviors are carried out with wireless communication. The Two-Step Fuzzy Optimization system has produced fuzzy logic parameters that cause robotic movements to be robust and smooth to avoid obstructions. In general, it can be said that the design of telemedicine robots works with good performance.

Some research topics can be suggested further, such as localization, positioning and mapping the location of robots, developing robot manipulators, or can also design a multi-robot for telemedicine robots.

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Author's Contributions

Andi Adriansyah: Coordinates all research activities, working on the optimization design process on fuzzy logic parameters and other robot control works.

Nanda Ferdana: Working on prototype robots, both hardware and software, manages the robot maneuverers and retrieves data.

Setiyo Budiyanto: Doing on remote control work via internet telecommunications between the GUI and the robot.

Julpri Andika: Helped working on prototype robots, both hardware and software, set up a camera capture and presentation system.

Ethics

This article is original and contains unpublished material. The corresponding author confirms that all of the other authors have read and approved the manuscript and no ethical issues involved.

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