Controlling Water Jet Based on Fuzzy Controller for Cleaning and Massage Patient's Head

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***Abstract*—Cleaning and massaging the head is a daily basic need of each person to ensure good health. This is especially important for patients whose immune system is weaker than the healthy people, this makes them vulnerable to external agents. Patients with difficult mobility have difficulty cleaning and washing themselves, they need the support from nurses and nursing staff, which can cause overcrowding in hospitals, especially as the world faces an aging population and COVID-19. Therefore, service robots applied to take care of patients have been increasingly interested in research. This paper proposed a serial manipulator that uses the pressure of a water jet to clean and massage the patient's head. A robot with 3 DOF creates a flexible trajectory so that the water jet can reach any point on the head. The robot is especially safe because it uses a water jet as the end-effecter instead of mechanical parts. The pressure impacting the scalp from water jet is varied by adjusting the water flow and the flow controller based on the fuzzy controller. The controller input variable is the variability between the measured flow value and the set flow value and returns the PWM pulse value to control the linear flow valve. Experimental results show the reliability of the flow fuzzy controller. The system's response signal is no overshoot as well as low error and the response time is fast enough.**

***Index Terms*—sphere robot, massage robot, shower robot, fuzzy controller, water jet**

I. Introduction

Massage and shampooing are the daily essential need of every person. Shampooing and massage help to clean the scalp and limit the accumulation of sebum on the scalp. The sebum is a favorable environment for pathogens such as bacteria to enter the body. Especially the patient, this bacteria causes more unwanted diseases and reduces the patient's ability to recover. Shampooing and massage help the patient both feel comfortable, reduce stress, create a positive impact on the patient's ability to recover. The research on using robots for massage is developed in many studies. A study is carried out to see if robots could be used to massage humans by assessing the pleasure level of the participants [1]. Participants are those who have little contact with robots. Massage by others, massage by a robot, and self-massage were the three stages that participants went through. Then, participants completed a survey at the end of each stage. The experiment's findings revealed that using robots in human massage had a lot of potentials. Currently, the world is facing an aging population that continue to increase in the future, which leads to significant demand for health services [2]. Not only that, the incidence of stroke is increasing not only in the elderly but also in young people. Those who are fortunate enough to receive timely treatment also suffer many sequelae later on, such as paralysis, or those who have many injuries that affect movement after a traffic accident. Such patients require care from the hospital's doctors and nurses in personal hygiene. With the increasing number of such cases, the problem of overcrowding will occur in hospitals, this causes the quality of care to decrease.

Therefore, the service devices and robots applied to take care of patients have been paid special attention by researchers. Those studies can partly reduce the workload and the overload in the hospital. Using a parallel robot mechanism to massage according to the trajectories on the human back is proposed in the study [3]. Besides, researchers have proposed single-use pads for washing patients' hair at the bedside instead of diapers [4]. A 6-DOF shampooing robot is equipped with fingers that can scrub the head area of the patient. The arms of the robot can control the pressure exerted on the patient's head area [5]. A massage robot based on traditional Chinese medicine was developed. The humanoid TCM massage robot has functions that can simulate artificial massage, movements such as kneading, rolling, and vibration used to treat pain in patient's waist and legs [6]. However, very few products focus on the problem of shampooing combined with acupressure massage in the head area for patients. Although shampoo products currently combined with acupressure massage, do not have high accuracy in taste point location.

Currently, massage with water jet pressure is gradually gaining popularity, there are some studies on the application of water jet in massage [7-9]. Water jet massage brings many benefits, helping patients relax, relieve pain, muscle tension, congestion in the venous and lymphatic systems. Not only that, but it also stimulates blood circulation and metabolism and loosens the subcutaneous tissues. Washing your hair with small jets of water is like taking a shower, the small jets of water will stimulate the acupuncture points on the head, helping to

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reduce headaches, and at the same time reduce stress. Combining the problem of hair washing and water jet massage, this paper has been proposed a robotic arm with an automatic hair washing function for patients combined with head acupressure massage based on traditional Vietnamese medicals. The robot carries high-pressure water jets to act on the patient's head for the purpose of washing and massaging. Because the water jet is a direct impact on the patient's head instead of the mechanical part, this robotic system is safe to use. A flow fuzzy controller was proposed with the purpose of controlling the pressure that the water jet creates. The pressure that the water jet creates is changed depending on the location of the acupressure point that the water jet moves to for a ma**ss**age.

II. Theory of Waterjet in Therapy

A high-pressure water jet is produced by moving a large volume of water under high pressure through a small nozzle. Water out of the tube at high speeds and exerts a force based on cross-section and pressure through the pump [10]. Overall, a water jet has been commonly used in medicine, ranging from massage to orthopedic surgery. The water jet has many applications in medicine and achieves many achievements. As a modern surgery, waterjet can replace conventional surgery due to water's properties as well as advantages that traditional surgery does not have. Most operations today are conducted in a conventional manner by a doctor who must be highly skilled. The use of scalpels in surgery has many disadvantages. Such as a big knife cut may cause scarring after surgery or cross-contamination of the doctor via wounds. Normal surgeries require a significant amount of time and effort on the doctor. Using water jets through modern machines provides many benefits to a surgical operation. Thanks to powerful control algorithms and advanced technology, the precision and size of the water jet are produced with minimal error. From there, we can make water jets of varying sizes for a variety of applications. There was a study that looked at waterjet nephrectomy. The study was carried out on 24 patients with diseases such as renal cell carcinoma, kidney stones, complex cysts and cancerous cell cysts. 24 patients underwent open surgery by water jet. The results obtained after surgery do not affect the intrarenal vessels, the surgery time is short and the blood loss is minimal during the surgery and especially, there is no tissue damage caused by heat. The results suggest that the water jet dissector is a useful tool for nephrectomy in organ removal surgery [11].

In medicine, using water jets in surgery brings more benefits than traditional methods. The cutting process generates only a small amount of heat so that the surrounding tissue is not affected by heat, injury is avoided, the depth and width of the cut can be controlled with high precision. The application of water jet combined with modern machinery in surgery, it provides a constant cutting force during movement, which is difficult to do by hand. At the same time, waterjet cutting leaves a clean wound, reduces bleeding, and shortens surgery time. A special feature of the water jet is that during cutting will produce low heat which is the most influential factor on the object being cut. The temperature can change the structure of the object to be cut, especially human bone which is one of the sensitive parts with heat [12].

In daily life, shampooing is the cleaning of hair by washing hair with water and shampoo solution, or other detergents. The purpose of shampooing is to clean the hair and scalp. Regular shampooing not only helps us to ensure aesthetics but also helps us to prevent some diseases related to the scalp [13]. Not cleaning the scalp regularly can cause sebum accumulation which makes the scalp more prone to dust, and makes hair tangled. In particular, the sebum on the scalp is also an ideal living environment for many types of bacteria. Those bacteria can enter the human body and causes the disease. For patients, they can slow down the recovery for the patient. Not washing your hair regularly also makes the scalp have an unpleasant odor. The pores are infected, there is an unpleasant odor and the hair is easy to fall out. Shampooing also helps us to feel comfortable and reduce stress. Therefore, washing hair is really an important issue. Using water jets in massage is one of the treatments of hydrotherapy. This method uses heat and pressure generated from small water jet to act on the whole body or in small areas. These water jet massage systems include high-pressure jets, the water jet acts directly on the patient's body to create stimulation on the skin's surface in order to help treat a number of diseases for the patient. The water jets act on the acupressure system on the human body just like using your hands to press and massage, thereby treating of some diseases.

III. Structure of System

The robotic arm used for cleaning and massage must touch any point on the head area, so the robotic arm has a spherical workspace. The proposed robot has 3 DOF in 2 directions of rotation around the X-axis and the Y-axis and the water jet is the third DOF. The robot's 2 links have a semi-circular shape that encloses the human head. Therefore, the robot can be minimized the number of links and the cumulative error can be minimized in the process of controlling the position. The robot structure is simulated as shown Fig. 1. Two links of the robot are made of stainless steel. The first link of the robot is a semi-circular stainless-steel bar with a rigidly welded round shaft in the center of the round frame with radius r. A motor is directly attached to this axis, this is the link that helps the robot to rotate around the X-axis with angle γ_1. With the second link of the robot, one end of the second link is attached directly to the motor, the other end is connected to a passive joint and rotates in the direction of the active joint. The two ends of the second link are connected concentrically to ensure synchronization of rotation angle and rotate around the y-axis with angle γ_2. On the second link, there are many nozzles with small diameters (from 1-2mm). The water jets are the end-effectors that act on the scalp according to pre-programmed trajectories.

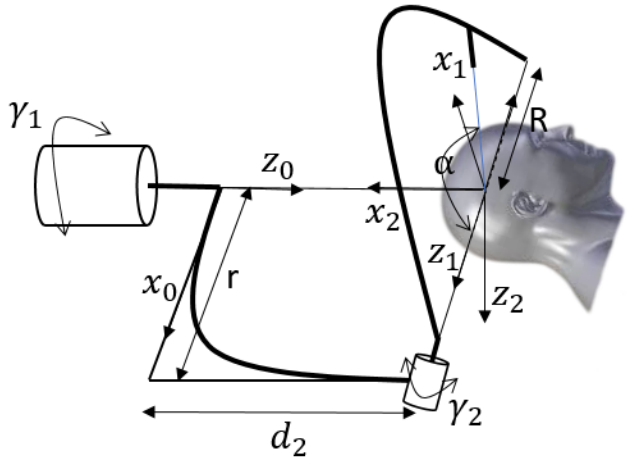


Figure 1. Mechanical system structure

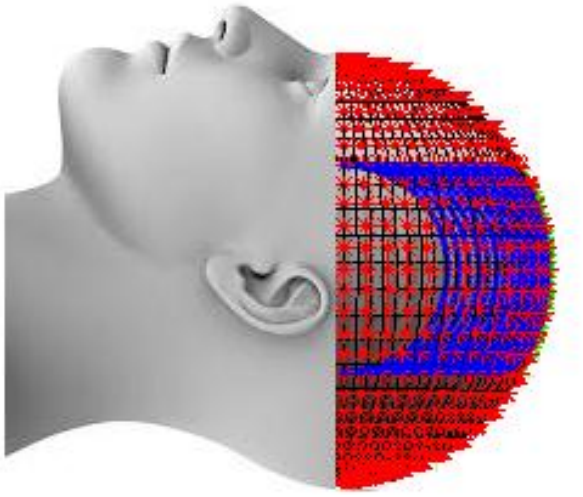


Figure 2. Workspace of three water jets

The water jets are kept at a fixed angle α and always ensure that the direction of the water jet is always directed towards the center of the patient's head. Workspace is an important requirement when designing robots. Workspace determines the operating range of different types of robots in order to determine whether the robot can satisfy the working requirements. The robot's workspace helps the designer to easily implement safety measures for the user. To determine the work space, first of all, the forward kinematic of the robot has to be determined. The paper uses the Denavit - Hatenberg method to calculate the forward kinematic. The coordinates of the points where the water jet affects the patient's scalp according to the reference Cartesian axis system is shown as follows (1-3)

$$P_x = r(\cos\gamma_1 \cos\alpha + \sin\gamma_1 \cos\lambda_2 \sin\alpha) \quad (1)$$

$$P_y = -r(-\sin\gamma_1 \cos\alpha + \cos\gamma_1 \cos\gamma_2 \sin\alpha) \quad (2)$$

$$P_z = d_2 + r\sin\gamma_2 \sin\alpha \quad (3)$$

From the forward kinematics equation, the inverse kinematics equation is determined. We simulated the robot's workspace to have the most intuitive view. The robot's workspace is shown in Fig. 2. With this structure of the robot, it allows the water jet can reach any point in the patient's head.

IV. Flow Controller with Fuzzy Logic

A. Fuzzy Logic and Theoretical Basis

Fuzzy logic [14] is developed from fuzzy set theory to perform the approximation argument instead of an exact argument like classical logic. In this sense, fuzzy logic uses approximate inferences and approximations to evaluate a problem, thereby making a rational decision in an uncertain environment. In two-valued logic, there is only true or false, but in fuzzy logic, the proposition can be true or false, or have intermediate values. Fuzzy logic is currently being applied in many fields, used to diagnose in medicine, finance, and especially to apply fuzzy logic in process control applications.

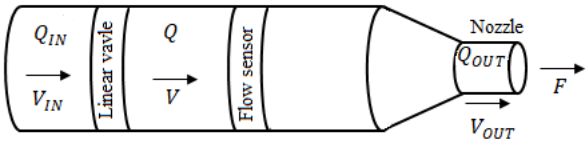


Figure 3. High pressure water jet system.

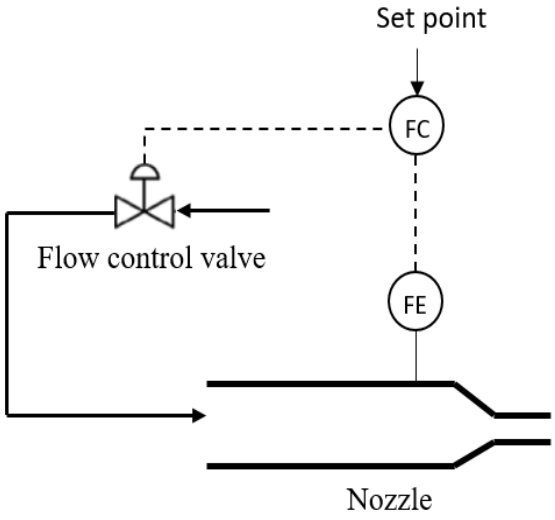


Figure 4. The flow control diagram.

What makes fuzzy logic special is that it doesn't require a rigorous theoretical argument like classical logic. Fuzzy system logic usually includes the following steps: fuzzy process, knowledge base, fuzzy inference, and defuzzification process. In this part, the fuzzy controller is designed to control the magnitude of the force of the water jet in the system. Fuzzy logic play a major role in creating the right voltage to control the linear valve or pump velocity, from which we can adjust the water flow to change the force of the water jet when it is out of the nozzle. A high-pressure water jet is a high-speed water jet

that is formed when water flows through a small diameter nozzle. The velocity of the water jet depends on the pressure before and after the jet exits the nozzle. The high-pressure pump is the heart of the system. The high-pressure pump increases the pressure of the water stream. The water after being pressurized is flowed into the high-pressure pipeline, flows through the linear valve, then passes through the nozzle at high speed (Fig. 3). Normally, the inner diameter of the nozzle is much smaller than the inner diameter of the high-pressure pipe, therefore the velocity when the water exits the nozzle is much higher. The water supply has to be sufficient and clean, this is also very important in systems using high-pressure water-jet. The velocity of the water flow before it flows out of the nozzle is controlled by a linear valve, this valve is managed by a central CPU and operated by a controller.

Where: Q_{IN} is the input water flow supplied to the system (m^3/s); Q is the water flow after flowing through the flow control valve (m^3/s); Q_{OUT} is the flow of water before exiting the nozzle (m^3/s); F is force of water jet (N).

The flow of the water stream is given by the equation (11).

$$Q = a.V \tag{4}$$

Where: Q is water flow (m^3/s); a is conduit cross-section(m^2); V is flow velocity(m/s).

Next is the formula for calculating the force when the water exits a cross section .

$$F = \rho.a.V_{OUT}^2 \tag{5}$$

Where: F is force of water jet (N); a is cross-sectional area where the water jet exits (m^2); V is flow velocity(m/s).

From two equations (11-12) for calculating flow and output force, it shows the relationship between flow rate and output force. When the flow rate changes, the force generated also changes. Therefore, instead of using the force variable directly for the control system, we use the flow variable as an input variable for the system, which is shown in the flow control diagram in Fig. 4. This makes the calculation easier, as well as convenient for the hardware installation of the system.

B. Define Input and Output Variables

An Error variable is used as input to the fuzzy flow control system. The variable Error = Set Point - Measured Value, is determined by the difference between the set value and the measured value on the system. In which, Set Point is the value that the system wants to achieve, Measured Value is the actual measured value on the system. The fuzzy control system is based on the variation of the Error variable to make a decision to control the system. The control object here is the flow variable. To be able to change the flow value, we change the opening of the flow control valve. The valve is controlled by a linear signal 4-20mA or 0-10VDC, when the analog signal input to the valve changes, the opening angle of the valve also changes. Therefore, the output variable of the system is the PWM signal that is supplied to the linear valve.

C. Membership Function

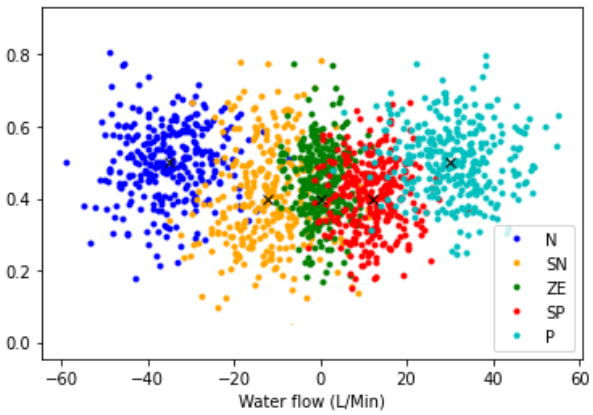


Figure 5. Error membership function

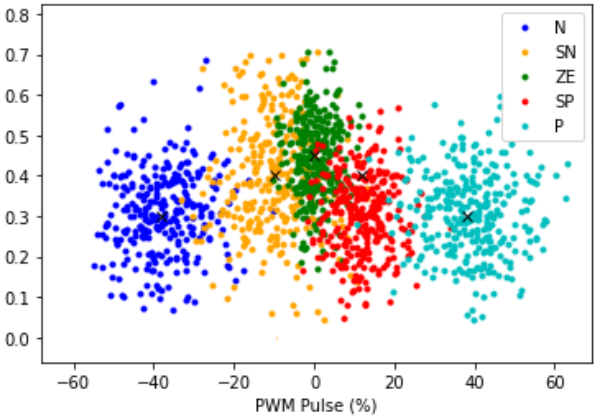


Figure 6. PWM variation membership function

A fuzzy set is represented by its membership functions. The membership functions [15] can be graphed. There are many types of graphs for membership functions such as triangular function, trapezoidal function, Gaussian function. In which, triangular function has the advantage of being simple, easy to implement and fast for calculation. However, the type of membership function is not an important factor influencing how the model behaves. The model is more influenced by the number of membership functions because it affects the computation time. The model can be optimized by changing the number of membership functions and the type of membership function.

Fuzzy input for the above system is Error = (*Set Point - Measured Value*). For fuzzified input, triangular function are used, fuzzy variable Error is divided into the following fuzzy intervals: N =negative, SN=small negative, ZE= zero, SP=small positive, P= positive. Member functions depend on the maximum system flow provided by the booster pump. Membership function of error variable is shown as Fig. 5. In this case, the maximum throughput received from the system is 60 (L/min). In order to control the water flow, the system used a linear valve, so the fuzzy output variable of the system is the variation of

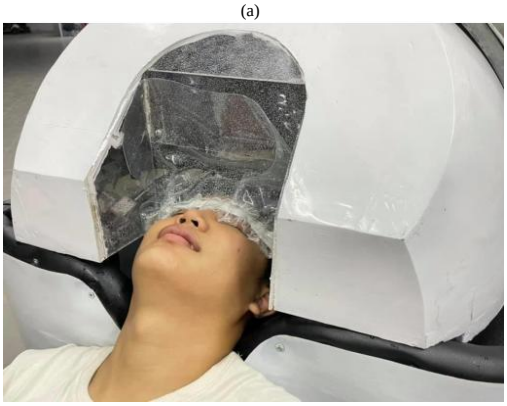
PWM supplying to the valve as shown in Fig. 6. This fuzzy variable is divided into fuzzy intervals as follows N = negative, SN = small negative, ZE = zero, SP = small positive, P = positive and use triangular function.

D. Control Rules

When the current values of the input variables are fuzzified, the fuzzy system proceeds to the step of making a decision depending on the specific case of the input variable, called the rules of a fuzzy logic system. In the rules section, the 'IF' section describes the situation where rules are expected. The following 'THEN' section describes the response of the fuzzy system in this state. The PWM pulse generation to control the valve follows these fuzzy rules. The water flow is adjusted by changing the opening of the linear flow valve. The system relies on the Error variable to give the appropriate PWM pulse variability value. The Error value represents the degree of variability between the measured flow value and the set value. When the error of the system is larger, the opening angle of the linear valve is also changed by a larger angle and vice versa.

V. Results and Experiments

(a)



(b)

Figure 7. The robotic mechanism in reality (a) The structure of system, (b) application on the human.

In the actual robot structure, the second link of the robot consists of 2 frames in the shape of a semi-circle, in which there is a frame divided into 3 compartments which are powered by 3 different water sources to facilitate the switching process and control the jet of water. The robot's second link is used to transport soap or water while washing hair. This link is a blank tube and have many nozzles. The frames in the second link can move at a 180-degree angle and move independently of each other, so the water jets can reach any point on the user's head. The radius of the 2 frames in stage 2 is 400mm and 440mm respectively with each frame including 3 nozzles. The robot is limited in motion by the outer frame of the system, so it is safe for the user. The system uses a DC servo motor to drive the joints of the mechanism. The robot arm mechanism is controlled by a separate microcontroller, the system uses a separate microcontroller to receive and process signals from the sensor block. Microcontrollers communicate with each other through the UART interface. The robotic mechanism in reality as shown Fig. 7. The massage system is based on the force that the water jet creates when the water jet exits the nozzle, the magnitude of this force depends on the flow rate before the water jet exits the nozzle, or it can be considered that the jet force depends on the water flow before out the nozzle. For the actual system, the team measured the maximum flow of water after it passed through the booster pump, which was about 60 liters per minute.

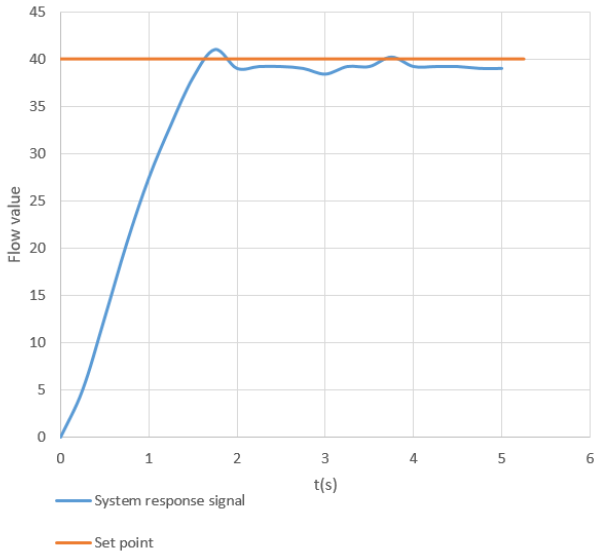


Figure 8. System response graph

With a sampling time of 0.25 seconds, the system receives a response after the set value of 40 liters/min. The graph in Fig. 8 shows the responsiveness of the system. The system is stable with a flow value of approximately 39 liters per minute, with an error of 1 liters per minute. The feedback does not overshoot, but there is an error from the desired value, and feedback occurs an oscillation phenomenon. The system stabilizes after a period of time t = 4s, this response time is completely in line with the head washing and massage requirements of the robot because the massage process focuses on massaging each point on the head and the time for each massage is about 1-2 minutes depending on each acupressure point. The robot's implementation is divided into two stages: head cleaning and head massaging. For the hair washing process, the robot is moved to the patient's position. the patient will be adjusted to the appropriate lying position to conduct hair washing and

massage. In the first step of the washing process, the patient head is wetted completely by the robot with clean water. Then the robot will spray a diluted shampoo solution over the patient's head to ensure that sebum and debris are removed. Finally, the patient's head will be cleaned again with clean water. At the end of the shampooing process, the robot will massage the patient head. High-pressure water jets will impact force on each acupuncture point on the head, each massage process includes many different acupuncture points depending on the patient's symptoms. Massage time and impact force depend on each acupressure point.

Proposing an automatic head shampooing and massage system with satisfactory results. The application of water jet in medicine is used in many systems of traditional medicine, during the outbreak of the covid19 epidemic, the health of humans needs to be improved and paid more attention. The massage system using water jets helps to reduce the possibility of disease spread in the present time, helps people relax, helps patients to be washed and massaged to be able to speed up the recovery in some patients. The system has the ability to switch on and off different water jets to minimize the probability of water jets entering dangerous acupuncture points. The system will be developed to adjust the parameters and apply them to actual hospitals to help reduce costs and reduce the strain on the medical staff. Adjust the force of the water jet according to each patient's requirements on the basis of permission by the doctors, making the patient feel more comfortable after being shampooed and massaged the head.

VI. Conclusions

The paper proposed a robot with the function of washing and massaging the head for patients with mobility difficulties. A robotic arm with 2 degrees of freedom of rotation is proposed, the robot uses the water jet as the end-effector to act directly on the patient's head for the purpose of washing and massaging. The application of robots to clean and massage patients brings many positive aspects. This robot reduces the amount of labor needed in hospitals and helps avoid the cross-infection of unwanted infectious diseases during the process of patient care. At the same time, during the outbreak of the Coronavirus, the use of robots helps to limit cross-infection among us while still ensuring the essential needs of patients. The magnitude of the force generated by the water jet in the massage system is controlled by the fuzzy logic controller by varying the water flow. The controller uses the difference between the set value and the measured value on the real system to make decisions to increase or decrease the opening angle of the linear valve, thereby changing the value of water flow.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

N.T.T.H performed the document preparation, data coll ection; N.T.T.H analyzed the results and wrote the first dr aft of the manuscript; the manuscript was revised by N.T. T. All authors contributed to conceptualization and design of the study structure and content; all authors had approve d the final version.

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