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An Energy-Efficient Variable Frequency Suction System for Floor-Tiling Robots Using A Fuzzy Logic Controller

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Abstract: Developing autonomous floor-tiling robots that can effectively manipulate floor tiles remains a critical research goal in pursuing enhanced operational efficiency and reduced worker fatigue. These robots are engineered to replicate the tasks performed by skilled tilers, employing a suction mechanism to independently grasp and precisely place substantial tiles with high accuracy. Although various robotic suction systems have been devised, the rigidity of traditional control logic controlling suction mechanisms potentially leads to superfluous energy consumption and operational inefficiency. The present study proposes an innovative variable-frequency suction control system in response to this technological impasse. This system equips a floor-tiling robot to adjust the suction force adaptively, thereby conserving energy. The objective of this research is the development of an effective fuzzy logic controller (FLC) tasked with regulating the gas flow of the closed loop. The design of the FLC system is predicated on vacuum adsorption dynamics, with inputs derived from negative pressure, which represents air pump intensity, and the change rate of the negative pressure, which indicates gas leakage speed. The output is the motor's duty cycle, which influences energy consumption. The FLC's membership functions and decision-making rules were determined by considering the equipment configurations, floor tiling requirements, and energy consumption requirements. The findings reveal that the FLC's adaptive modulation of the air pump's flow rate substantially curtails the power consumption of the floor-tiling robot. Consequently, this outcome contributes to a novel control paradigm that could be integrated to augment contemporary construction robotics' intelligence and energy efficiency.

Keywords: Construction robot; Floor tiling; Fuzzy logic controller; Vacuum adsorption

1 INTRODUCTION

To enhance the aesthetic appeal, provide durability, ease of maintenance, and improve hygiene for buildings, floor tiling serves as a critical element in both residential and commercial projects (Silva et al. 2017). A well-tiled floor not only creates comfortable, stylish, and functional living spaces, but also plays a vital role in ensuring safety, cleanliness, and compliance with industry standards and regulations (Grönqvist 2011). Traditionally, the task of floor tiling has been carried out by skilled workers who manually lift heavy tiles, apply adhesive, and meticulously place each tile on the floor surface (Nguyen et al. 2021). However, this labor-intensive process is not only time-consuming but also poses significant challenges to workers' health and well-being. The repetitive nature of the work, combined with the need to handle heavy materials, can lead to worker fatigue, musculoskeletal disorders, and an increased risk of injuries (Boschman 2012, Abas et al. 2018). Moreover, the quality of the finished tiling work is heavily dependent on the skill and experience of the workers, which can result in inconsistencies and imperfections in the final product, ultimately affecting customer satisfaction and project success (Swami and Kadiwal 2020).

In an effort to address these challenges and improve the efficiency and quality of floor tiling operations, developing a robotic system with suction mechanisms to automatically lift and place floor tiles has been seen as a promising solution (Liu et al. 2018). For example, Ali and Esra developed a rectangular manipulator with a suction cup assembled on a pneumatic cylinder for mosaic tiling. Three stepper motors drove the suction system to accomplish three-dimensional movements along the XYZ coordinates. The vacuum system and the pneumatic cylinder were controlled by a 120 MHz DSP microprocessor, which receives the communication commands through the RS232 serial port (Oral and Inal 2009). To reduce the work intensity of workers while improving the efficiency and the quality of floor tiling, (Shun et al. 2021) developed a robotic system with a mobile platform, a robotic arm, and a vacuum adsorption end effector to automate the floor tiling process. By sending various PWM (Pulse width modulation) signals, a vibration motor was driven to power the vacuum end effector.

Despite the successful implementation of robotic systems in lifting and placing tiles, current vacuum systems are primarily powered by electronic motors, which may lead to inefficient energy consumption. Typically, these motors rapidly reach their peak power output upon activation and maintain this level of operation throughout the entire working cycle, resulting in significant energy inefficiencies and excessive power consumption (Caracas et al. 2013). Moreover, the motors are often selected for specific working requirements, challenging and accommodating customized needs. For instance, when completing floor-tiling tasks in an apartment, large tiles are commonly used in living rooms, while smaller tiles are preferred in bathrooms. In such scenarios, although the selected high-powered motor may be suitable for suctioning the large tiles, it can lead to energy inefficiencies when tiling smaller tiles, as the motor's output cannot be easily adjusted to match the specific requirements of each task (Mahmud et al. 2020). To address this issue and improve the energy efficiency and intelligence of robotic suction systems, the present research aims to propose a variable frequency suction system for floor-tiling robots by designing a fuzzy logic controller. Design details of the fuzzy set, membership functions, decision-making rules, and defuzzification methods are depicted in the following sections.

2 METHODOLOGY

2.1 Design of Fuzzy Logic Controller

Figure 1 simplifies the designed FLC system. The fuzzification process first transformed the crisp input of closed-loop negative pressure and the rate of negative pressure change into the linguistic labels by computing the crisp value with membership functions. The decision-making rules were then made considering the working effectiveness of the suction system to map the linguistic input with the linguistic output. During the defuzzification process, the linguistic output was transformed into crisp values through membership functions to control the rotation of the servo motor and, therefore, power up the air pump to suction floor tiles. Details of the design of input and output, membership functions, and decision-making rules are depicted in the following contents.

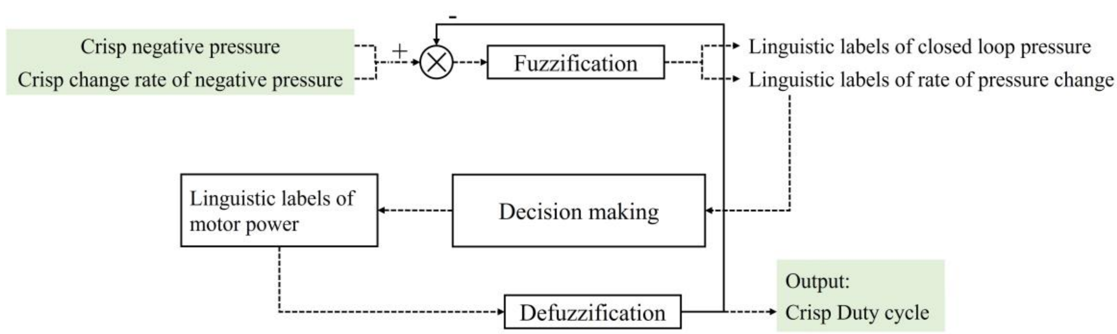


Figure 1: Design of the FLC system

2.1.1 Design of Input Data

In the designed FLC system, the closed loop pressure and rate of pressure change were determined as the input data, and the motor power was determined as the output data.

The design was proposed according to the working principle of the suction system. Utilizing the underlying principles of vacuum adhesion, a vacuum pump continuously extracts air from an enclosed circuit, consisting of an air pump, gas transmission tubes, and suction cups, thereby diminishing the circuit’s internal gaseous pressure beneath the ambient atmospheric pressure. A servo motor was connected to the air pump to configure its impeller or piston. A vacuum state is generated when the gaseous pressure inside the closed circuit is lower than the outside atmospheric pressure, allowing the suction cups to adhere to a tile securely. During the suction process, the vacuum pump's air extraction efficacy can be represented by observing the real-time closed-loop pressure, which was quantified using negative pressure values. When the negative pressure value increases, the pressure within the closed-loop system decreases, denoting a robust suction capability; conversely, when the negative pressure value decreases, the pressure within the closed-loop system increases, signaling a reduced evacuating velocity and compromising the suction device's capacity to elevate the tile. Specifically, the relationship between the negative pressure value and the pressure inside a closed loop is calculated using Eq. 1.

$$P_{negative} = P_{atmospheric} - P_{closedloop} \quad \text{(Eq. 1)}$$

Here, $P_{negative}$ refers to the negative pressure value (expressed as an absolute value), $P_{atmospheric}$ refers to the atmosphere pressure (1 standard atmosphere (atm)), $P_{closedloop}$ refers to the actual pressure inside the closed-loop system.

While a higher negative pressure correlates with a firmer attachment of the tile, an overly significant negative pressure decrease might lead to unnecessary energy dissipation or even damage to the tile. Consequently, it is feasible to avoid an undue reduction in pressure and circumvent extra energy consumption by dynamically adjusting the rotation of the motor, encompassing both deceleration and halting. The suction cup and the tile are not hermetically sealed, and gas leakage may occur upon the motor's deceleration or cessation. Monitoring the rate of negative pressure change facilitates a quantitative evaluation of the gas leakage conditions. In instances where the rate of pressure change is too high, which indicates the gas leak too fast, it is essential to expedite the motor's rotation and augment the suction effort to ensure the tile's secure attachment. Alternatively, when the rate of gas change is acceptable, which indicates the gas leakage is insubstantial, and pressure levels remain within the desired parameters, it is advisable to decelerate the motor, thereby effectively balancing the adhesion of the tile and energy conservation.

The motor's power output is a critical factor that directly affects the operational performance of the air pump, which in turn regulates the pressure within a closed-loop system. The motor power was selected as the FLC system's output to control the working efficacy of the air pump and adaptively adjust the pressure and the rate of pressure change. The motor power was adjusted by sending various duty cycles of pulse width modulation (PWM).

2.1.2 Design of Membership Functions

After determining crisp input and output variables, membership functions were regulated to transform the crisp values to the linguistic labels and their fuzzy degrees. According to the design of the FLC system, three fuzzy sets of closed-loop negative pressure, rate of pressure change, and motor power were included. Membership function types and linguistic labels were detailed when designing the membership functions.

(1) Membership function types

To seamlessly represent the uncertainty and ambiguity of the pressure adjustment process and provide a natural gradual transition, the most adopted membership functions of triangular and trapezoidal functions were employed (Zadeh 1965). Using the triangular and trapezoidal functions, the fuzzy degree of crisp closed loop pressure, rate of pressure change, and motor power can be calculated with Eq. 2 and Eq. 3, respectively.

$$f(x;a,b,c) = \max\left(\min\left(\frac{x-a}{b-a}, \frac{c-x}{c-b}\right), 0\right) \quad \text{(Eq. 2)}$$

Here, $f(x;a,b,c)$ refers to the fuzzy degree of the crisp values. x refers to the crisp values. a,b,c refers to the left limit, the right limit, and the central point of the triangle.

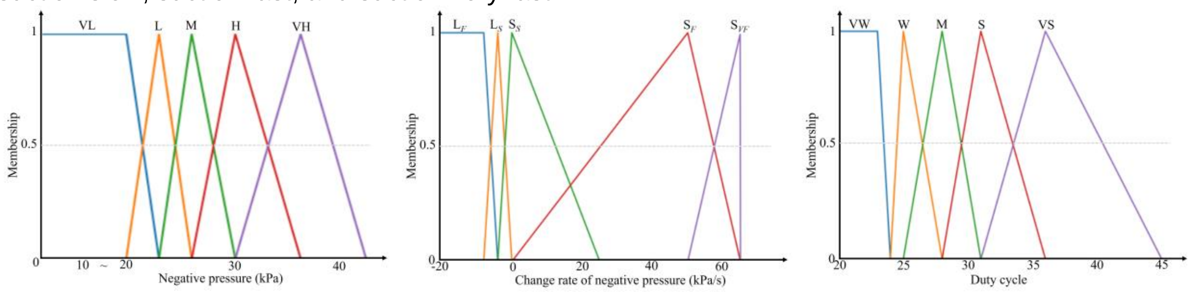
$$f(x;a,b,c,d) = \max\left(\min\left(\frac{x-a}{b-a}, \frac{d-x}{d-c}\right), 0\right) \quad \text{(Eq. 3)}$$

Here, $f\left(x;a,b,c,d\right)$ refers to the fuzzy degree of the crisp values. x refers to the crisp values. b,c refer to the shoulder of the trapezoidal, a,d refer to its feet.

(2) Linguistic labels

As mentioned, the inputs of the FLC system are negative pressure, and the rate of negative pressure changes, while the output is the duty cycle. By computing the crisp input and output values using the membership functions, their fuzzy degrees corresponding to the regulated linguistic labels can be obtained, which are uniformed into a fuzzy range [0,1].

Referring to the previous studies that focused on designing an FLC system for electro-pneumatic devices (Oguntosin et al. 2017), the fuzzy range of inputs and outputs was separated into five semantic variables, respectively, shown in Figures 2. The corresponding fuzzy subsets for closed loop pressure, rate of pressure change, and motor power were defined as {VL, L, M, H, VH}, {L_F, L_S, S_S, S_F, S_{VF}}, and {VS, S, M, F, VF}, where VL, L, M, H, VH express the negative pressure inside the closed loop is very low, low, medium, high, very high, respectively; VW, W, M, S, VS express the duty cycle of PWM is very weak, weak, medium, strong, very strong, respectively. During the air pump operation, the system is engaged in a suction mode, amplifying the negative pressure change within the closed loop. A positive rate of change characterizes this increment in negative pressure. In contrast, the cessation of the air pump's function initiates a state of gas leakage, during which there is a reduction in the negative pressure values. This reduction manifests as a negative rate of change in the negative pressure within the closed loop. Therefore, the linguistic labels of L_F, L_S, S_S, S_F, and S_{VF} express leak fast, leak slow, suction slow, suction fast, and suction very fast.



(a) Membership function of negative pressure

(b) Membership function of change rate of negative pressure

(c) Membership function of duty cycle

Figure 2: Membership function of inputs and output

The limits and intervals of the fuzzy degrees for the linguistic labels were established initially based on the equipment configurations and suction requirements, and further refined through a series of experiments. The minimum limit of the negative pressure fuzzy set was determined by considering the size of the suction cups, the weight of the suctioned floor tiles, and the initial suction state, as expressed in Eq. 4. To meet the essential requirements of floor tiling tasks involving commonly used tiles weighing 2.5kg, the present study employed an air pump with a DC motor, incorporating a safety factor of 10, and colloidal suction cups with a diameter of 40mm. The maximum limit of the negative pressure fuzzy set was set at 50kPa, corresponding to the motor's maximum power output configuration. However, to achieve precise control and efficient energy saving, the maximum limit was reduced to 42kPa based on observations from several fine-tuning experiments. The fuzzy interval between 20kPa and 42kPa was divided equally, adhering to the principle of equal division.

$$P_{\min} = \alpha_i P_{negative} = \alpha_i \left(\frac{m_i g}{n A_i}\right) \quad \text{(Eq.4)}$$

Here, $P_{\min}$ refers to the minimum limit of the negative pressure. α_{i} refers to the safety factors of the *i-th* motor. g refers to the acceleration of gravity. m_{i} refers to the weight of the floor tiles. n refers to the number of suction cups. A_i refers to the area of each suction cup.

As depicted in Eq. 5, the first derivative of the negative pressure value was utilized to represent the change rate of the negative pressure, where $\dot{P}$ denotes the negative pressure value at time *t*.

Consequently, the upper and lower limits of the change rate fuzzy set were determined to be -20 and 65, respectively. Considering the instantaneous inertia of the leakage and suction states, the interval of the change rate fuzzy set was designed to be compact within the "L_F, L_S" and "S_F, S_{VF}" fuzzy ranges. In contrast, the intervals corresponding to the "SS" and "SF" fuzzy labels were designed to span a wider range. This approach ensures that the fuzzy logic controller can effectively capture and respond to the dynamic changes in the negative pressure while accommodating the inherent inertia present in the system.

$$\dot{P} = \frac{df}{dx}(x_0) \tag{Eq. 5}$$

The minimum and maximum limits of the motor's PWM duty cycle fuzzy set, ranging from 0 to 50, were initially determined based on the specifications of the DC motor commonly employed for operating vacuum pumps. However, through testing experiments, the maximum limit was refined to 45. Experimental observations revealed that when suctioning floor tiles, the motor's power predominantly fell within the range of 24 to 36. To enhance the dynamic response and precision of the FLC system, the interval was designed to be more compact within the 24 to 36 range.

2.1.3 Decision-Making Rules

To establish the decision-making logic for mapping inputs, which exhibit varying degrees of membership in the negative pressure and change rate of negative pressure fuzzy sets, to outputs in the motor power fuzzy set, fuzzy rules were formulated. The modus ponens considered the most fundamental form of fuzzy rule (Dubois and Prade 1984), was adopted. A modus ponens fuzzy rule takes the canonical form: IF x is A THEN y is B, where x represents the input variables, and y denotes the output variable. The linguistic labels A and B are associated with the respective fuzzy sets characterizing the input and output variables. To connect multiple antecedents in the rule premises, t-norms (Ashraf et al. 2019) were employed as the conjunction operator and the logical AND connector. For instance, a fuzzy rule can be expressed as IF negative pressure is VL AND rate of change is L_F, THEN motor power (PWM duty cycle) is VS.

The fuzzy rule base was formulated by considering two pivotal factors influencing the suction system's operation: functionality and energy consumption. The rules were designed to ensure the system's ability to effectively suction floor tiles while simultaneously optimizing energy utilization by modulating the motor power based on the negative pressure and its rate of change within the closed-loop circuit:

(1) To ensure the successful suction of floor tiles by the suction system, it is imperative to maintain a relatively high negative pressure within the closed-loop circuit. This can be achieved by increasing the PWM duty cycle of the DC motor, which in turn enhances the operational capacity of the air pump to continuously suction and sustain an air pressure inside the closed loop that is lower than the ambient atmospheric pressure.

(2) A negative rate of change in the negative pressure indicates a gas leakage issue. In such cases, to maintain the desired air pressure differential within the closed-loop circuit, increasing the motor's operational intensity is necessary, corresponding to higher PWM duty cycle values.

(3) If the negative pressure is at a very high level, it indicates there is enough negative pressure inside the closed loop, it is redundant. It is possible to decrease motor power by outputting a lower PWM duty cycle to suction the floor tiles up and save energy consumption at the same time.

(4) A high positive rate of change in the negative pressure implies that the motor is operating at an intense level, sufficient for successfully suctioning the floor tiles. In this scenario, there is no need to maintain the higher operational intensity. It is advisable to decrease the PWM duty cycle output at that moment to conserve energy as much as possible.

Table 1 presents the fuzzy rule base formulated based on the aforementioned principles governing the suction system's operation. The validity and feasibility of each fuzzy rule listed in the table were experimentally verified by evaluating the suction system's performance during validation trials.

Table 1: Established fuzzy rules

	VL	L	M	H	VH
L_F	VF	VF	F	F	M
L_S	VF	F	F	VS	S
S_S	F	F	M	S	S
S_F	F	F	S	S	VS
S_{VF}	M	M	S	VS	VS

2.1.4 Defuzzification Method

The defuzzification process is account for translating the fuzzy motor power obtained from the decision-making engine into crisp values of PWM duty cycle that can be used for controlling the air pump operation. One of the most widely adopted defuzzification methods, the centroid method (Mitsuishi 2022), was employed. The computing process is shown in (Eq. 6):

$$PWM_{centriod} = \frac{\sum_i \mu(p_i) p_i}{\sum_i \mu(p_i)} \quad \text{(Eq. 6)}$$

Here, $PWM_{centriod}$ refers to the output crisp PWM duty cycle. $\mu(p_i)$ refers to the membership value for *i-th* fuzzy set. p_i refers to the centroid point of *i-th* fuzzy set.

2.2 Validation Experiment

To assess the functionality and energy consumption of the designed fuzzy logic system, an on-site experimental setup was established, as depicted in Figure 3. The suction system consists of essential components, including suction cups, an air pump, and detection sensors. Four suction cups were strategically placed at the corners of the floor tile to maximize the suction system's coverage area. A high-performance air pump with a rated power of 24W, a negative pressure of -75 kPa, a positive pressure of 120 kPa, and a flow rate of 18 L/min was utilized to generate negative pressure within the closed-loop circuit. The air pump and suction cups were interconnected using a network of hoses to facilitate gas transmission, with the red arrow in Figure 4 indicating the gas flow direction within the closed-loop circuit. All hose terminations, including the connection points with the suction cups, were carefully sealed to minimize gas leakage.

A DC motor with a rated power of 42W and a negative pressure capacity of -85 kPa was employed to drive the air pump. The fuzzy logic controller was integrated into the system to dynamically adjust the motor's duty cycle based on real-time measurements of the negative pressure and its rate of change. This approach aimed to optimize the suction functionality while simultaneously minimizing energy consumption. By continuously monitoring and adapting to the system's performance, the fuzzy logic controller ensures that the suction system operates efficiently and effectively throughout the floor-tiling process.

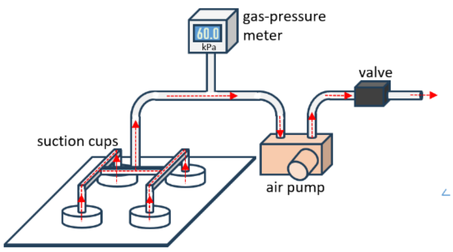


Figure 3: Experimental suction system

The input variables of negative pressure and its change rate were monitored in real-time using a gas pressure meter. An analog conversion module in a programmable logic controller (PLC) was employed to acquire the negative pressure data from the pressure meter. The acquired negative pressure data was transmitted to a personal computer (PC) via the TCP/IP communication protocol. The PC was responsible for computing the change rate of the negative pressure and executing the designed fuzzy logic algorithm based on the received negative pressure data. The computed crisp PWM duty cycle output was ultimately transmitted to the motor through the RS485 communication protocol to control the motor's power and the air pump. To minimize gas leakage within the closed-loop system, an electronic valve was installed at the air pump outlet to block the airflow when the air pump was not in operation. When the air pump starts working and the pressure meter detects negative pressure inside the closed loop, the electronic valve automatically opens to allow airflow through the hoses. The detected negative pressure was sent to the electronic valve by the PLC, which received the pressure meter’s output and transmitted the pressure data to the electronic valve through an IO signal. The energy consumption of the system can be calculated using the electronic power calculation principle, as expressed in Eq. 7.

$$E = PT = VIT \quad \text{(Eq. 7)}$$

Here, E refers to the energy consumption. P refers to the instantaneous motor power, t refers to the motor operation time. Ohm’s law and the definition of power, the instantaneous motor power, can be obtained by computing the instantaneous voltage (V) and current (I). A current voltmeter was employed to monitor the voltage and current of the suction system, which were sent to the PLC through the RS485 communication protocol. The signal communication diagram is simplified in Figure 4.

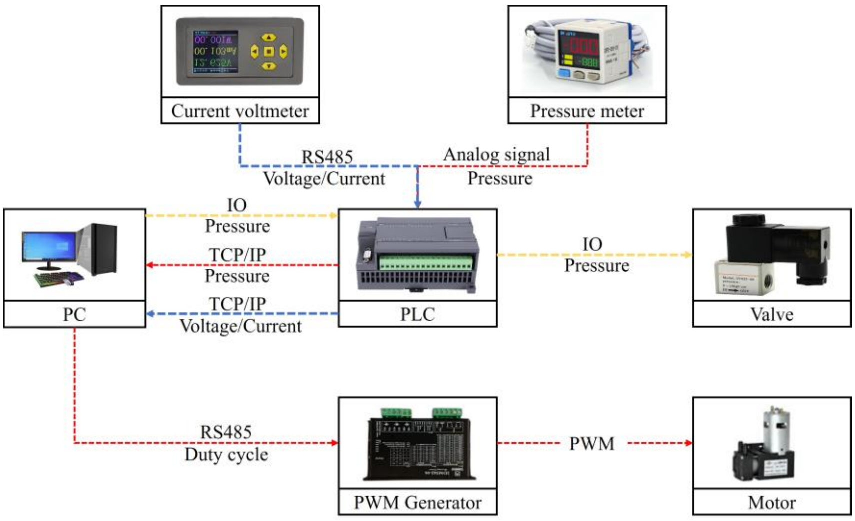


Figure 4: Signal communication diagram

A series of experiments were conducted to simulate the suction task for a typical floor to assess the performance of the designed FLC system. The floor tile dimensions were 300x300 mm, weighing 2.5 kg. The suction system was tested under two distinct operating conditions: (1) a constant PWM duty cycle of 24, representing the minimum required duty cycle to prevent motor blockage, and (2) an adaptive PWM duty cycle regulated by the fuzzy logic system. The functionality and energy consumption of the FLC-regulated suction system were evaluated by comparing its performance against the constant 24-duty cycle benchmark. This comparative analysis aimed to assess the efficacy of the designed FLC system in terms of its ability to maintain suction functionality while optimizing energy utilization.

3 RESULTS

The testing results, depicted in Figures 5 and 6, validate the successful implementation of the designed fuzzy logic controller (FLC) system, enabling the suction system to exhibit frequency conversion capability. As illustrated in Figure 5, both the negative pressure outputs obtained by controlling the motor with a constant duty cycle and the FLC-regulated duty cycle exceed the minimum safety suction negative pressure (calculated using Eq. 4), indicating the successful suction of the floor tile. Meanwhile, when operating the motor at a constant duty cycle of 24, the negative pressure within the closed-loop circuit remained at approximately 27 kPa. The negative pressure curve exhibited obvious fluctuations upon regulating the suction system with the designed FLC system, with minimum and maximum points of 20 kPa and 32 kPa, respectively. This behavior indicates that the FLC system automatically fuzzified the instantaneous negative pressure and generated the corresponding fuzzified output based on the designed fuzzy rule base. For instance, at the 5-second mark, when the negative pressure reached 31 kPa, corresponding to a fuzzy degree of “H” or “VH,” the output duty cycle decreased with a fuzzy degree of “S” or “VS,” causing the motor to cease operation and conserve energy. Consequently, the negative pressure experienced a sharp decline to 20 kPa. Conversely, when the negative pressure decreased to 20 kPa, with a fuzzy degree of “VL” or “L,” the FLC system triggered a sharp increase in the negative pressure from 20 kPa to 32 kPa during the 6-7 second interval by outputting a duty cycle corresponding to “F” or “VF.” This action ensured that the air pump operated at a high intensity to suction the air, preventing the floor tile from falling.

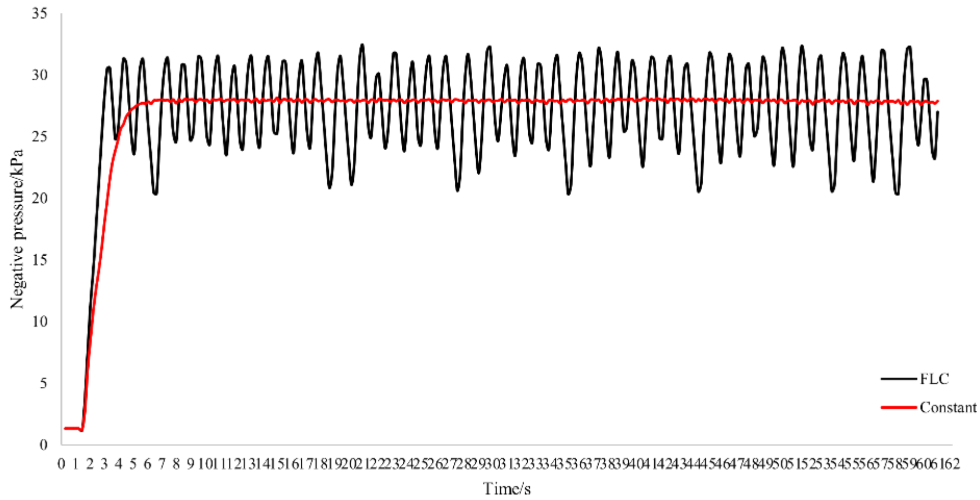


Figure 5: Comparison of negative pressure

Figure 6 illustrates the variation in the rate of change of the negative pressure. The results demonstrate the successful implementation of the FLC system in enabling the suction system to operate with variable frequency suction and deflation cycles. When controlling the motor with a constant duty cycle of 24, no significant variations in the rate of change were observed, with the values fluctuating within a small range of (-3, 3). However, suction and deflation cycles became evident upon regulating the suction system with the designed FLC system. For instance, at the 6-second mark, the rate of change reached a low point of -13, corresponding to a fuzzy label of “L_F.” Concurrently, the duty cycle output was at the “F” or “VF” degree, instructing the air pump to operate at a higher intensity to prevent the floor tile from detaching. Consequently, the rate of change experienced a sharp increase to 13 at the 7-second mark, indicative of a suction behavior. This dynamic modulation of the suction intensity, facilitated by the FLC system, ensured the maintenance of the desired negative pressure differential within the closed-loop circuit, enabling effective suction and lift of the floor tile while optimizing energy consumption through variable frequency operation.

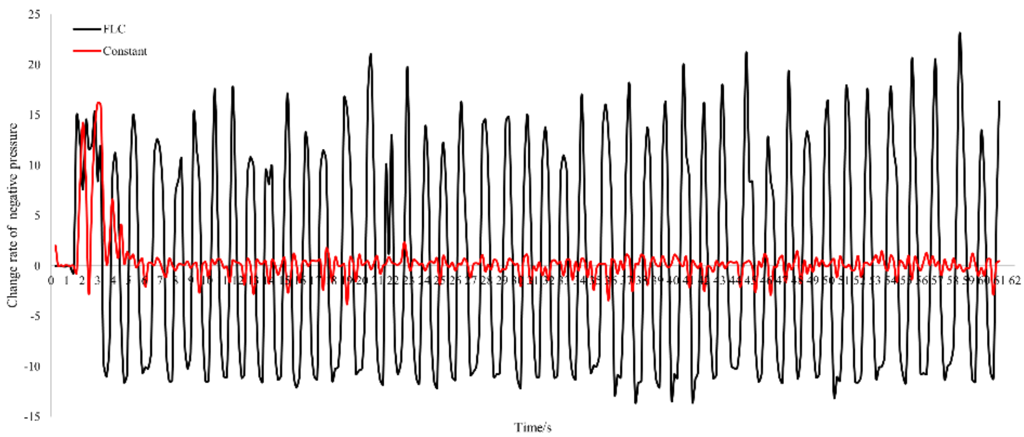


Figure 6: Comparison of Change rate of negative pressure

To validate the energy consumption behavior, 30 experimental floor tiling suction trials were conducted, representing a feasible number of experiments to validate the observed phenomenon (Hill 1998). In each trial, the suction system was operated continuously for 1 minute. Table 2 presents the energy consumption results obtained by controlling the motor with a constant duty cycle of 24 and the FLC system-regulated duty cycle, respectively. The results demonstrate that regulating the suction system with the designed FLC system leads to a noticeable reduction in energy consumption. The energy consumption values for all 30 experiments involving the FLC system-regulated duty cycle were lower than those with a constant duty cycle, with minimum and maximum energy savings of 130J and 5J, respectively. The energy-saving performance became more pronounced as the suction system's operating duration increased. After subjecting the suction system to a continuous floor tiling operation for 15 minutes, the energy savings reached 1435J, with the suction system controlled by a constant 24-duty cycle consuming 19186J, while the FLC system-regulated suction system consumed only 17751J.

Table 2: Energy consumption comparison

Experiment	FLC(J)	Constant(J)	Saving(J)	Experiment(J)	FLC(J)	Constant(J)	Saving(J)
E1	1064	1139	75	E16	1052	1155	103
E2	1020	1150	130	E17	1057	1137	80
E3	1090	1148	58	E18	1111	1144	33
E4	1091	1149	58	E19	1133	1151	18
E5	1085	1153	68	E20	1101	1128	27
E6	1081	1148	67	E21	1060	1162	102
E7	1040	1140	100	E22	1088	1145	57
E8	1093	1133	40	E23	1093	1148	55
E9	1050	1148	98	E24	1045	1138	93
E10	1066	1140	74	E25	1026	1145	119
E11	1095	1133	38	E26	1103	1135	32
E12	1143	1148	5	E27	1033	1135	102
E13	1071	1144	73	E28	1040	1128	88
E14	1134	1142	8	E29	1022	1138	116
E15	1087	1150	63	E30	1012	1148	136

4 CONCLUSION

To improve the adaptivity, intelligence, and energy saving of the existing suction mechanism for floor tiling robots, this study proposed a variable-frequency suction system by designing a fuzzy logic controller (FLC) system. The inputs of the FLC system are the negative pressure inside the suction closed loop circuit, as well as the change rate of the negative pressure. The output is the duty cycle of the motor's PWM, which indicates the instantaneous energy consumption. The fuzzy sets, membership functions, and decision-making rules were defined based on the equipment configurations, floor-tiling requirements, and energy-saving conditions. The centroid defuzzification method was employed to output crisp duty cycle commands. A series of on-site testing experiments were conducted to validate the feasibility of the designed FLC system. The results show that the FLC system successfully enables the suction system with variable-frequency ability. There is an apparent energy saving compared to controlling the motor with a constant intense duty cycle. The research outcomes allow the suction robots to adjust energy consumption dynamically based on real-time requirements. However, following limitations are worth investigated: 1) the fuzzy rules and membership functions were established based on empirical knowledge and experimental testing, which may not yield the most accurate control strategy. 2) The experimental equipment lacks airtightness, which has a significant impact on the pump's efficiency. To solve the limitations, future research intends to focus on: 1) Investigating the incorporation of genetic algorithms or neural networks to objectively define the fuzzy system, potentially leading to enhanced energy-saving performance. 2) Improving the structural airtightness of the equipment, resulting in more substantial energy savings. Additionally, future work could focus on optimizing the fuzzy algorithm to increase its adaptability and generalizability, enabling its application in a broader range of construction robots, such as automated excavators and tower cranes, to achieve energy conservation in various construction tasks.

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