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Design and construction of an automatic syringe injection pump

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ABSTRACT

Today, the world is witnessing more interest in robotics and their application in various fields, such as medicine. Enhancing accuracy, increasing speed of operation and reducing costs are the primary performance objectives in the improvements to design and manufacture of devices or robots. One of the best ways to achieve these aims is using devices or robots instead of human resources. The injection pump we designed and manufactured in this work is a type of robot that has applications in medicine and health centres. This device is used for patients who are unable to receive foods and drugs orally. By examining similar foreign devices in Ardebil health centres, studying their advantages and disadvantages, and researching health centre requirements for these devices, we designed and constructed such a device for the first time in this country. The most important items achieved in these investigations include time, accuracy, speed of drug injection and cost reduction. The shortest time we achieved using this device was approximately 6 s for 1 cc of drug or fluid. We also calculated the speed of injection for 1 cc of drug to be approximately 0.17 cc per second, which was an ideal value compared to that of similar foreign devices. In comparison to the cost of similar foreign devices, our device has a lower cost due to simplicity and high performance. To achieve these results, we designed a new device engine. In this design we used a three-step engine that has a different algorithm than similar devices. In this engine, every cc was injected in 2000 steps of the engine, and each step was 3 ms, achieving 6 s for each cc of injection.

1. Introduction

Syringe injection pumps for therapeutic or diagnostic purposes are used for the slow injection of drugs. These devices are also used for injection of blood components, such as plasma. The syringe injection pump consists of a fluid bag and a clamp or a hook that is hung at the top of the pump with a tube connected. Inside the pump, the tube, which is filled with fluid, is fixed on some small gears and a roller. When the roller rotates and the gears move, the fluid transfers from the tube to the patient. The user adjusts the fluid flow and required volume through the device, so the gears and roller move based on the adjusted speed. Every time the required volume of fluid is released, an alarm sounds, and the fluid flow stops. The tube passes through an air detector sensor, and when air bubbles are detected, the alarm sounds, and fluid flow stops. The syringe injection pump monitors the fluid pressure rate, resulting in fluid pressure control, which avoids excessive injection pressure on the patient's vein and possible pain at the injection site. If excessive pressure is detected, due to tube obstruction, an alarm will inform the user. Thus, the speed and accuracy of injection of a given amount of drug at a predetermined time, without using human resources, as well as the health of intensive care patients, were found to be important. The plastic syringe containing fluid is placed in a holder, a tube and the holder are set with a needle or cannula (?), and both are connected to the patient's vein or directly to the stomach. When the rate of the fluid flow was indicated, the pump placed pressure on the syringe plunger to push fluid into the injection site. The rate of injection (plunger movement) depends on the syringe diameter and the adjusted flow rate of the pump. High or even

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low injection dosages of a specific drug can be dangerous for patients. Plastic syringes manufactured by different companies are not identical; therefore, pumps are adjustable to work with different syringe models. All types of usable syringes are specified by labels on the device. Substantial errors in flow rate changes and fluid volume are observed when unauthorized syringes are used. Using syringe injection pumps controls injected fluid pressure and avoids damaging the patient's vein due to excessive injection pressure. High pressure will result in an alarm and injection tube obstruction. The measurement units are millilitres per hour (mL/h), and typical values are 0–250 mL per hour. The first attempt at manufacturing an intravenous therapy device was conducted in 1492. Then, this branch of medical sciences progressed slowly, until the first injection device was produced by Christopher Ren in 1658. Then, many experiments were performed using this syringe, and better syringes were developed. These experiments led to patient death, and syringe production was stopped for a while. When the production ban was lifted, the first samples of adjustable pumps for controlled drug injection into veins were made. In the 20th century, empty bottles were used instead of plastic bags, which reduced the blood flow in contact with air. Major developments occurred in 1970, when Dean Came invented the first ambulatory injection pump. This pump was connected to the patient for treatment while the patient was being moved. This device helped diabetic patients who needed injections at appropriate times. These pumps also released a certain quantity of a drug over a certain length of time. The injection pumps developed during this time period have manual and electronic records for the alarms. These pumps will also alarm if they become stuck during an injection. To avoid drug errors for high-alert medications, smart pumps are used in intensive care units. Foreign injection pumps are portable devices that continuously inject drugs into patients. These pumps are the size of a cassette player and are attached around the patient's waist. These devices are powered by batteries. Drug delivery pathways for these pumps are intravenous, subcutaneous, epidural, internal and in the spinal cord. This device is used for morphine injection and other strong painkillers to control intensive pain and chronic cancers. Annually, the Medicinal and Health Regulatory Agency (MHRA) reports safety incidents related to injection devices. After ten years of investigating such incidents [3], showed that in more than 50% of incidents, there is no device error, and user error accounts for 19% of incidents. Several studies have investigated continuous injection of drugs for treatment of radiolopsey. Anaesthesia trials by drug injection via the epidural catheter and via bolus injection only for neck radiocolopsey were conducted. These studies showed that the epidural catheter is more efficient than injection alone [2] also studied radiocolopsey by epidural catheter and injection pump. They found that the injection pump is more efficient than a catheter system. They found that complications in the syringe pump were not significant [1] studied a continuous epidural block with steroids and anaesthesia connected by an infuser (???) to the epidural catheter. They also found no significant complication in this method. An injection pump was used for continuous or alternate injection of a drug, and the injection pathways included intravenous, subcutaneous, epidural, and spinal cord pathways. These pumps have been placed in an infraclavicular block and a catheter to the desired position. Catheter position and spinal cord pathways are used for spinal cord injuries. Drug transmission includes the circular motion mechanism, osmotic pressure, combination of the osmotic pressure with an oscillating piston and layer fluoride fuel. This mechanism is used for the initial treatment of liver cancer, neck cancer, chronic pain and refractory and metastatic colorectal cancer. In a double-blind study, Banergi et al. evaluated the effect of an injection pump on a small amount of bupivacaine drug. This study neither supported nor rejected the use of an injection pump. Based on the working conditions of a syringe pump, research has found that it should be resistant to water penetration. Different standards are imposed to express water resistance; the most reliable is IPX, which is expressed using a number between 0 and 4. IPX: 0 is the least resistant to water penetration, and 4 is the most resistant. In Europe, Japan and the USA, manufacturing companies are obliged to engrave this standard so that it is visible to the consumer (often on the device label) because it is considered a critical issue for syringe pumps. In many prestigious hospitals, not paying attention to this issue has caused broken devices and even fire during operation. Popular brands in Iran are often made by Japanese companies, but you can also find brands from the USA, Germany and Brazil. The most famous of these companies are BB, Atom and JMSTerumo, and device costs differ according to the manufacturer and device features; costs range over one million tomans between these four companies.

We used CC/S unite in this project.

2. Methods

2.1. Design and construction of an automatic injection syringe pump

In this project, design and construction were carried out in three steps. First, we made the electronic parts of the device as explained in the third section, then we programmed the artificial intelligence parts of the device, and then the mechanical parts were designed. Most of the time, these three parts were constructed simultaneously. At the beginning of the project, we surveyed the use and performance of similar foreign devices at the Ardebil hospitals and ambulances in the city. By visiting the medical equipment support departments in these hospitals, we compiled advantages and disadvantages of these devices and scrutinized their failures. Based on this work, we designed a similar domestic device. We made this device at low cost and with different construction algorithms in our dear country. We present the construction of this device, its parts, the formulas and diagrams, and manufacturing of the circuit board. We explain the results of our new design in tables.

3. Results

3.1. Experimental results based on the design and construction of a new injection device

Experimental results indicate that for the 60 cc syringe used in this pump, for every 2000 motor pulses, 1 cc of fluid is injected into the patient. Based on this injection rate, we studied the three-phase flow of the motor. In the experiment, the syringe column size was 92 cm, and the inner diameter of its coloured column was 2.5 cm. The top of the cells is open space, and the bottom is covered with a Teflon piston. We placed the fluid-filled 60-cc syringe in a pre-determined location. According to our observations, every cc of fluid injection required the engine to move 2000 steps. Every motor pulse is 3 ms, so we obtained the duration of a 1-cc injection for the patient and the speed of syringe movement from 1 cc to 60 cc based on the following formulas. To achieve this equation, we first needed to know the time required for the motor to move 2000 pulses. Based on the observation that every motor pulse is 3 ms, we have:

t: The time of movement for every motor pulse
t': The time required for 2000 motor pulses

Therefore, t′ is equal to:

Formula 1.

$$t' = t{*}2000\ \ p = 3ms\ {*}2000 = 6000\ ms = 6s$$

Thus, based on formula 1 for 2000 motor pulses, 6 s is required. It takes 6 s for the syringe to inject 1 cc. We have:

$$x_1 = 1cc \rightarrow 2000p$$

x_1: movement of 1 cc of liquid for injection
x_2: movement of 60 cc of liquid for injection

Thus, x_2 is equal to:

Formula 2.

$$x_2 = 2000p{*}60cc = 120000$$

Given that each cc of injection required 6 s, we calculate the drug injection time for 60 cc. According to formulas 1 and 2 we find:

Formula 3.

$$\frac{1cc}{60cc} = \frac{6s}{t_{60cc}} \Rightarrow t_{60cc} = 360s$$

Based on the $t_{1cc} = 6$ s, we have:

$$\bar{v} = \frac{\Delta x}{\Delta t}$$

Formula 4.

$$\Delta x = x_{60} - x_1 = 60 - 1 = 59cc$$

Formula 5.

$$\Delta t = t_{60} - t_1 = 360 - 6 = 354s$$

From formulas 4 and 5, the average speed per cc of drug injection is:

Formula 6.

$$\bar{v} = \frac{\Delta x}{\Delta t} = \frac{59}{354} = 0.166cc/s$$

Therefore, the average speed of the injection for 1 cc of drug is approximately 0.17 cc per s, providing a time of injection:

Formula 7.

$$x_1 = v_1 t_1 \Rightarrow 1cc = v_1{*}6s \Rightarrow v_1 = \frac{1}{6} = 0.166s$$

A volume-time graph for drug injection, according to formulas 6 and 7 and v = 0.17, is shown in Graph 1, which demonstrates the process of the fluid moving in the syringe.

When we change the speed to v = 0.34, the volume-time injection graph for this drug will change as shown in Graph 2:

Graph 2 is for the doubled speed.

Graph 2, volume-time graph when the speed is doubled

In addition, every step in the engine is completed in 3 ms, so:

Formula 8.

$$F = \frac{1}{T} = \frac{1}{3 \times 10^{-3}} \cong 334HZ$$

F is the frequency required to enable the motor and is the inverse of time for each step of the motor. In this formula, if we put in the shortest motor step time, we will get the maximum required frequency for step motion. F = 334 Hz is the maximum required frequency for step motion, and at higher frequency, the motor will become saturated. To find the minimum motor frequency, we must enter the maximum required time for each motor step. The maximum time required for each motor step is 10 s. Therefore, we have:

Formula 9.

$$F = \frac{1}{T} = \frac{1}{10 \times 10^{-3}} \cong 100HZ$$

Therefore, the shortest required frequency for this motor is 100 Hz. In addition, if the frequency is lower than this, the engine will be saturated.

Based on formulas 8 and 9, we conclude:

$$100 \leq F \leq 334$$

3.2. General schematic for the syringe pump device circuit board

As Fig. 1 shows, we have indicated the connection of the microcontroller with the device circuit board, LCD, motor and motor drive or transistor. We have indicated the microcontroller connection pins for the components.

We studied the connection of the device keyboard to the device microcontroller and present the results along with the numbers of microcontroller pins in Tables 1–4.

We studied the connection of the device LCD with the microcontroller shown in Figs. 1–3 and present the results based on pin numbers in this table.

We studied the device driver connection with the microcontroller based on Figs. 1–3 and present the results based on the microcontroller pin numbers in this table.

Table 4 presents the results from the first connection line with the base and the second connection line between the sensor and microcontroller. Both results are based on Figs. 1–3, and the table results are presented based on the microcontroller pin numbers.

3.3. Results from comparing 4-step and 3-step motors used in the device

As explained in Section 3, companies have used four-phase motors manufacturing syringe pump devices. Based on prior results using 4-step motors, we designed a cable capable of connecting to a 4-step motor according to the following table:

As indicated in Tables 4 and 5, in 4-step motors, if we move the motor clockwise, this will enable coil A and disable the other coils, and step 1 will be enabled. In the same way, by enabling coil B and disabling the other coils, step 2 will be enabled. By enabling coil C and disabling the other coils, step 3 will be enabled. To enable the 4th phase of the motor, we must enable coil D and disable the other coils. However, if the motor moves counterclockwise, these phases will be inverted; the first phase will be D, and then other phases will be enabled.

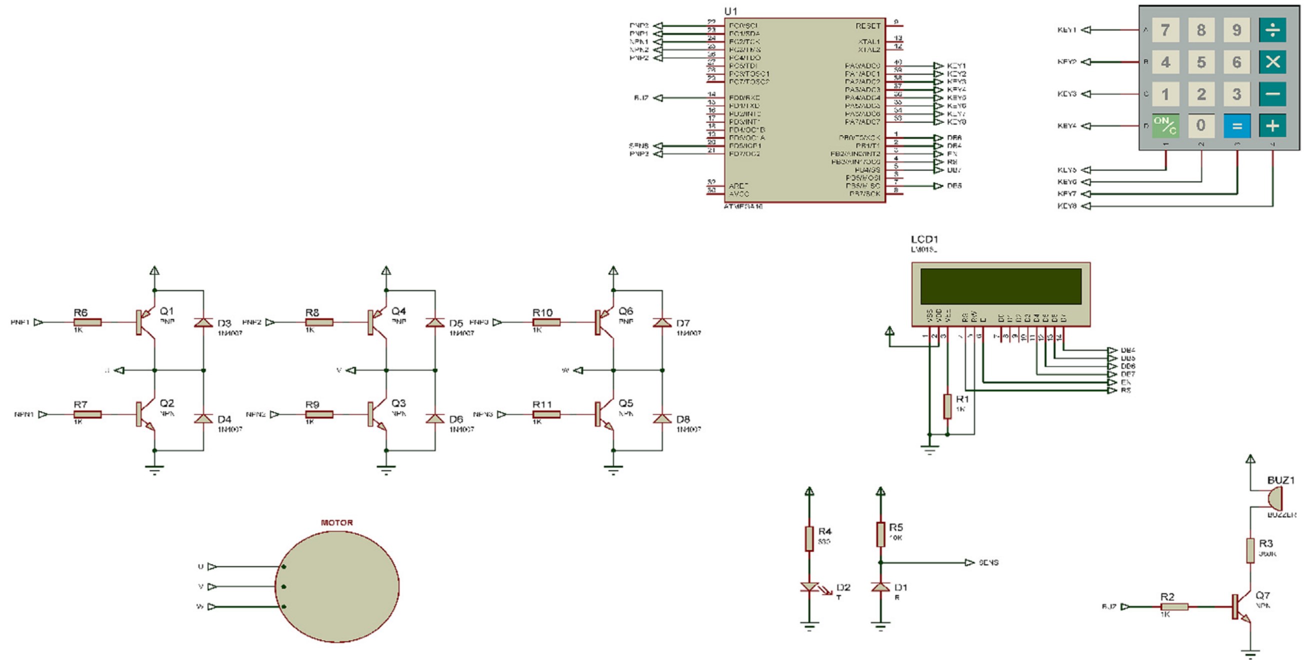


Fig. 1. Schematic view of the circuit of instrument and the connection of board items with microcontroller.

Table 1
Connection of the keyboard of the device with microcontroller.

Keyboard connection	Connected pins	Microcontroller connection
KEY1	40	PA0/ADC0
KEY2	39	PA1/ADC1
KEY3	38	PA2/ADC2
KEY4	37	PA3/ADC3
KEY5	36	PA4/ADC4
KEY6	35	PA5/ADC5
KEY7	34	PA6/ADC6
KEY8	33	PA7/ADC7

Table 2
Connection of LCD of the device with the microcontroller.

Connection of LCD	Connected pins	Microcontroller connection
DB6	1	PB0/T0/XCK
DB4	2	PB1/T1
EN	3	PB2/AIN0/NT2
RS	4	PB3/AIN1/OC0
DB7	5	PB4/SS
_	6	PB5/MOS1
DB5	7	PB6/MIS0
_	8	PB7/SCK

Table 3
Connection of driver of the device with the microcontroller.

Connection of driver	Connected pins	Microcontroller connection
NPN3	21	PD7/OC2
PNP3	22	PC0/SCL
PNP1	23	PC1/SDA
NPN1	24	PC2/TCK
NPN2	25	PC3/TMS
PNP2	26	PC4/TDO

Table 4
Connection of the device baser and sensor with microcontroller.

Baser and sensor connection	Connected pins	Microcontroller connection
BUZ	14	PD0/RXD
SENS	20	PD6/LCP1

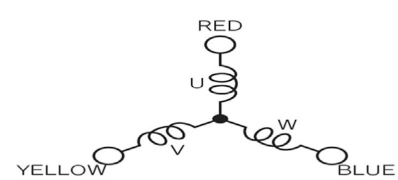


Fig. 2. Wiring connection of motor.

To manufacture our injection device, we used three-step motors; the cable connections to the motor are presented in Table 6.

Table 6 presents the three-step engines motion. For moving to the first step, the u phase is the red positive cable, the v phase is the yellow negative cable, and the w phase (blue cable) is neglected in the first step. Similarly, in the second motion step, u is neglected, v is negative, and w is positive. For the third step, u is negative, w is positive, and v is neglected. For the fourth step, u is negative, v is positive, and w is neglected. For the fifth step, u is neglected, v is positive, and w is negative. Finally, for the sixth step, u is positive, w is negative, and v is neglected. If this continues, the motor will move clockwise. For example, if we start the motor from the third step, as soon as it reaches the sixth step, it will return to the first step and then proceed to the second step. It will continue until the first step is done inversely and the three-step motion is counterclockwise.

In Fig. 3, we indicate the numbers of pins connected to the motor and cables and the size of cables and pins.

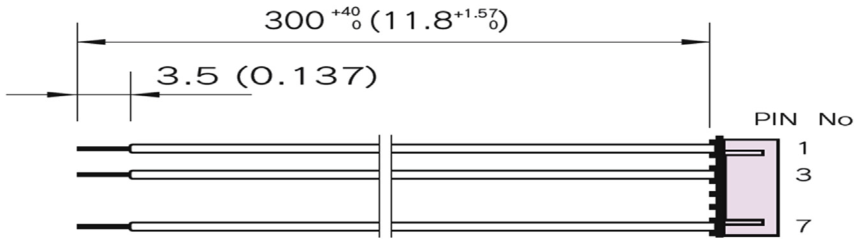
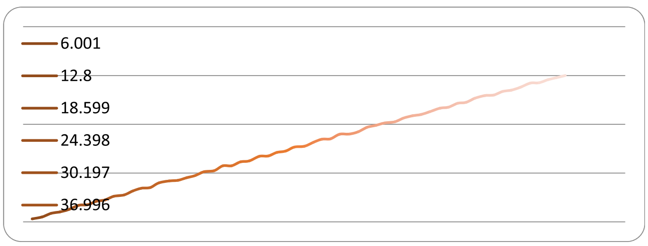
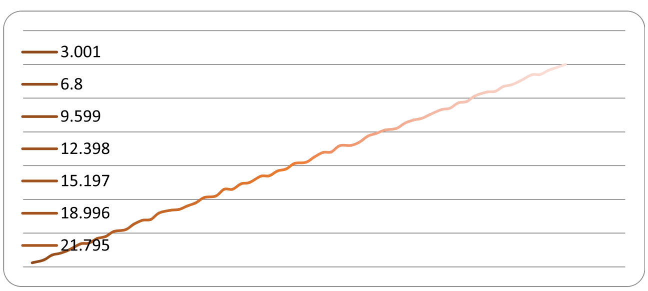


Fig. 3. Pin no. and size of wires connected to motor.



Graph 1. Time and space chart of injection 60 CC drug.



Graph 2. Time and space chart of drug injection with double speed.

Table 5
Cable of connection with motor in 4-step motors.

Clockwise	Step	Coil A	Coil B	Coil c	coil D	Counter clockwise
↓	1	1	0	0	0	↑
	2	0	1	0	0	
	3	0	0	1	0	
	4	0	0	0	1	

Table 6
Performance of connection cable with the motor in 3-step motors.

Phase	Step 1	Step 2	Step 3	Step 4	Step 5	Step 6
U	+		−	−		+
V	−	−		+	+	
W		+	+		−	−

Table 7
Colors of the three-step motor wires by pin numbers.

Pin No.	Wire color
1	Yellow
2	
3	Blue
4	
5	
6	
7	Red

In Table 7, the colours of the wires are indicated based on the pin numbers in Fig. 3. Pin 1 is the yellow wire, pin 3 is the blue wire, and pin 7 is the red wire.

4. Conclusion

According to results we obtained from construction of this device, we need 6 s for every cc of drug injection by this device. This injection time is approximately 2 s less than those of similar foreign devices, and no difference was observed in some comparisons. As outlined in the second section of this work, in some manufactured devices, the time is 2 s less than the time that we achieved. According to the formulas obtained in the fourth section of this work, the speed of injection for every cc of drug in this device was approximately 0.17 cc/s, which is more comparable to the injection speeds of some similar foreign devices. However, other foreign-developed devices, because they have 2 CPUs and higher processing power, had injection rates greater than that achieved by our device. By comparing the design of our device with those of foreign devices, we hypothesize that we can increase the injection rate by modifying our engine. Studying the microcontrollers and engines of these devices, especially three-step motors, and comparing injection rates will provide much-needed progress. However, we need to consider that due to sensitivity to drug injections, injection rates should not be more than those presented here; high injection rates can cause irreparable effects to the patient. To compensate for this deficiency, these devices should be rate-controlled for special drugs. Another point that should be considered is that, based on surveys conducted at health centres using these devices, attention needs to be paid to the design and construction of the injection pumps in terms of the mechanical and electrical components and the software. Electrical components, construction and placement of the circuit board on the body of the device need to be considered because according to surveys in Ardebil health centres, poor planning can cause fires at the time of drug injection to the patient, causing irreparable damages to both patient and hospital. In addition, mechanically, the frame or cover of the device used for most foreign devices is a durable compact plastic, and in this device, we used a 3 mill organic coating that is structurally weak; our device is a research sample, and there is a high cost for manufacturing a stronger frame. This will cause failure of the device if used for clinical usage in health centres. To improve this case, we propose a thicker organic coating, 10 mill, with strength and durability for use by the operator, which will reduce the danger of failure at the injection time. If the device fails at the injection time because of the sensitivity to some drugs, it will negatively affect the patient. Software deficiencies also have negative effects. In some cases in hospital surveys, pressing the wrong key could be dangerous to the patient, for example, entering several zeros instead of ones or entering the wrong quantity of a drug. Attention needs to be paid to the programming of this device so that a special alarm sounds for the user error. Other studies have indicated that some of these problems are related to user error. There should be an easy guidebook for the users and doctors, and users should have necessary training before use. We have presented a device that injects 1 cc of drug into the patient in a prescribed time, for example, 6 s, at a speed of 0.17 cc/s. This device is suitable for patients who cannot take medication orally; it is possible for them to take the medication through the blood using this syringe pump device. According to the results from section four, we present a three-step engine in designing this device. These motors have different algorithms compared to the four-step engines in similar foreign devices. By comparing these motors, we concluded that every cc of injection provided by three-step engines requires 2000 pulses. Accordingly, every motor pulse is 3 ms, and we need 6 s for injection in these three-step motors. This is an ideal time for injecting into a patient's vein via cannula. Additionally, one of the purposes in designing this device was a comparison to similar foreign devices. In foreign devices, injection of a liquid, for example, 50 cc, was accomplished at a certain speed, injecting into the patient continuously until 50 cc was emptied. However, our new device is adjustable; we can inject a quantity of liquid into a patient based on time by adjusting the injection rate.

Authors' Contributions: We present a robotic device that we designed and manufactured, which has applications in medicine and health centres. This device is used for patients who are not able to receive food and drugs orally. By comparing our device with similar foreign devices in Ardebil health centres and studying their advantages and disadvantages and researching the requirements of health centres for these devices, we designed and constructed an injection device for the first time in this country. The most important items achieved in these investigations include time, accuracy, speed of drug injection and reduced costs. The shortest time we achieved in this device was approximately 6 s for 1 cc of drug or fluid. We calculated the speed of 1 cc of drug injection to be approximately 0.17 cc per second, which is an ideal value compared to similar foreign devices.

Competing interests

The authors declare that they have no competing interests.

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