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Selection of executive drives of an automated robot manipulator for refueling vehicles

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Abstract

This study addresses the design and implementation of an automated robotic refueling system, aimed at enhancing efficiency, precision, and safety in the vehicle refueling process. Modern vehicle refueling points (VFPs) are evolving beyond traditional functions, incorporating digital technologies to streamline operations and improve customer experiences. The integration of robotic systems in this context has the potential to revolutionize fuel dispensing by minimizing human involvement and reducing the risk of operational errors. The proposed system utilizes advanced kinematic modeling, comparative actuator analysis, and the selection of suitable stepper motors to achieve precise and reliable manipulator performance. Electric drives, particularly stepper motors, were chosen over hydraulic and pneumatic alternatives due to their superior mass-size efficiency, precision, reliability, and adaptability to varying operational conditions. The inclusion of Internet of Things (IoT) technologies and artificial intelligence (AI) algorithms enables dynamic adaptation to different vehicle types and ensures seamless interaction between the refueling robot and the vehicle. Key methods employed include system analysis, kinematic diagram development, load and torque calculations, actuator selection based on technical specifications, and validation through simulation. The study demonstrates the feasibility of a fully automated robotic refueling system that minimizes the human factor and optimizes fuel delivery operations. Future work will focus on hardware prototyping, software development, and the integration of advanced sensors and control algorithms to further enhance system autonomy, adaptability, and safety.

Keywords: stepper motor, robot manipulator, kinematic scheme, kinemica, motor

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Көлік қызметі. Инженерлік іс және инженерия

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Көлік құралдарына жанармай құю үшін автоматтандырылған робот-манипулятордың атқарушы жетектерін таңдау

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Түйіндеме
Бұл зерттеу Көлік құралдарын толтыру процесінің тиімділігін, дәлдігін және қауіпсіздігін арттыруға бағытталған автоматтандырылған роботты жанармай құю жүйесін әзірлеуге және енгізуге бағытталған. Қазіргі заманғы жанармай құю станциялары (PTS) дәстүрлі мүмкіндіктерден асып түседі және жұмысты оңтайландыру және тұтынушыларға қызмет көрсету сапасын жақсарту үшін цифрлық технологияларды қамтиды. Осы контексте роботтық жүйелерді біріктіру адамның қатысуын азайту және операциялық қателер қаупін азайту арқылы отынды мөлшерлеу жүйесінде төңкеріс жасай алады. Ұсынылған жүйе манипулятордың дәл және сенімді жұмысына қол жеткізу үшін жетілдірілген кинематикалық модельдеуді, жетектерді салыстырмалы талдауды және сәйкес қадамдық қозғалтқыштарды таңдауды қолданады. Электр жетектері, атап айтқанда қадамдық қозғалтқыштар гидравликалық және пневматикалық баламалардың орнына олардың массалық тиімділігі, дәлдігі, сенімділігі және әртүрлі жұмыс жағдайларына бейімделуі үшін таңдалды. IoT технологияларын (IoT) және жасанды интеллект алгоритмдерін (AI) пайдалану көлік құралдарының әртүрлі түрлеріне динамикалық бейімделуді қамтамасыз етеді және жанармай құю роботы мен көлік құралының үздіксіз өзара әрекеттесуін қамтамасыз етеді. Қолданылатын негізгі әдістерге жүйелік талдау, кинематикалық схеманы әзірлеу, жүктеме мен моментті есептеу, техникалық сипаттамаларға негізделген дискіні таңдау және модельдеу арқылы тексеру кіреді. Зерттеу адам факторын азайтатын және жанармай беру операцияларын оңтайландыратын толық автоматтандырылған роботты жанармай құю жүйесін құру мүмкіндігін көрсетеді. Болашақ жұмыс аппараттық прототиптерді жасауға, бағдарламалық жасақтаманы әзірлеуге және жүйенің автономиясын, бейімделуін және қауіпсіздігін одан әрі жақсарту үшін озық сенсорлар мен басқару алгоритмдерін біріктіруге бағытталған.

Түйін сөздер: қадамдық қозғалтқыш, робот-манипулятор, кинематикалық схема, кинематика, қозғалтқыш

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Транспортные услуги. Инженерия и инженерное дело

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Выбор исполнительных приводов автоматизированного робота-манипулятора для заправки топливом транспортных средств

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Аннотация
Это исследование посвящено разработке и внедрению автоматизированной роботизированной системы заправки, направленной на повышение эффективности, точности и безопасности процесса заправки транспортных средств. Современные пункты заправки транспортных средств (ПТС) выходят за рамки традиционных функций и включают цифровые технологии для оптимизации работы и улучшения качества обслуживания клиентов. Интеграция роботизированных систем в этом контексте может революционизировать систему дозирования топлива за счет минимизации участия человека и снижения риска эксплуатационных ошибок. Предлагаемая система использует усовершенствованное кинематическое моделирование, сравнительный анализ приводов и выбор подходящих шаговых двигателей для достижения точной и надежной работы манипулятора. Электроприводы, в частности шаговые двигатели, были выбраны вместо гидравлических и пневматических альтернатив из-за их превосходной массогабаритной эффективности, точности, надежности и приспособляемости к различным условиям эксплуатации. Использование технологий Интернета вещей (IoT) и алгоритмов искусственного интеллекта (AI) обеспечивает динамическую адаптацию к различным типам транспортных средств и обеспечивает бесперебойное взаимодействие между роботом-заправщиком и транспортным средством. Основные используемые методы включают системный анализ, разработку кинематической схемы, расчет нагрузки и крутящего момента, выбор привода на основе технических характеристик и проверку с помощью моделирования. Исследование демонстрирует возможность создания полностью автоматизированной роботизированной системы заправки, которая минимизирует человеческий фактор и оптимизирует операции по подаче топлива. Будущая работа будет сосредоточена на создании прототипов аппаратного обеспечения, разработке программного обеспечения и интеграции передовых датчиков и алгоритмов управления для дальнейшего повышения автономности, адаптивности и безопасности системы.

Ключевые слова: шаговый двигатель, робот-манипулятор, кинематическая схема, кинематика, мотор

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Introduction

Today, vehicle refueling points (VFPs) are no longer just a place to fill up gasoline. They are service centers where a car can be serviced, spend a pleasant time with a cup of coffee, have a snack and buy necessary goods. But the improvement of technologies does not stop there, digitalization has not left traditional gas stations behind. Even now fueling of vehicles is realized at autonomous gas stations, where manual labor is minimized. Most gas stations are equipped with touch-screen devices and support mobile applications. In the conditions of modern reality, the presence of technologies is the norm. Their introduction is mainly aimed at making the refueling process fast, convenient and physically unburdensome for customers [1, 2, 3, 4].

The development of automation and robotization leads to a noticeable reduction of human resources in the service industry. Gas stations of the future are no exception: they will interact with applications at a deeper level, be equipped with smart dispensing guns, and even deliver fuel to the place and time specified by the customer.

In China, the USA and a number of European countries, pilot projects with “humanless” gas stations are already being implemented, where a car can be refueled in an automatic, robotic mode [3, 4, 5]. The driver only needs to park near the fuel dispenser, turn off the car, select the desired type of fuel and its quantity in the application. After that, the robot itself will open the hatch, pour the fuel and complete the process. Money is deducted from the account after the completion of refueling without additional actions on the part of the user, who receives a receipt by e-mail. Thus, the motorist does not even need to get out of the car, which is especially important in bad weather or when there is a threat of epidemics.

The authors of this article are working on the project of an automated, robotic gas station. It includes a set of mechanical and digital systems, when a robot with the help of a set of sensors tracks the position of the car, connects to it through cloud services of the “Internet of Things”, and with the help of a robot-manipulator refuels the car in the shortest possible time. Unlike foreign analogues, the authors of the project propose to minimize the presence of complex mechanical systems inherent in mechatronic systems. In spite of this in the designed filling station all working processes are absolutely automated, the human factor is minimized. There will be no drunken gas station attendant, who will “bang” the refueling gun on the fender of the car, nor a torn hose from the column, as the interface between the station and the car simply will not allow it to move while the refueling process is going on. There is also a “flexible” system of adjusting the dispenser to different makes and models of cars. The human factor is also taken into account - every driver will park near the column differently. Artificial intelligence algorithms allow to cope with this task. They help to accurately determine the position of the gas tank hatch, to refuel, to disconnect and close, controlling all parameters and recording deviations. Reliability in the refueling task is also important. The designed refueling robot can determine and calculate the required amount of fuel for each vehicle, preventing errors and fuel spillage.

Methods

In this study, a systematic approach was used to design and select the most suitable actuators for the manipulator links of the robotic refueling system. The following methods were applied:

System Analysis. The design process began with a comprehensive analysis of the requirements for the robotic refueling system. This included evaluating the operational conditions of the manipulator and determining the degrees of freedom necessary to cover the working area around the vehicle’s fuel tank. The system analysis defined the constraints and requirements for the mechanical and control systems.

Kinematic Modeling. A kinematic diagram was developed to visualize the manipulator's movement. The kinematic scheme considered both angular and translational movements, essential for accurately positioning the fuel nozzle. The model also accounted for the varying positions and angles at which different vehicles approach the refueling station.

Comparative Evaluation of Drive Types. Different actuator types (electric, pneumatic, hydraulic) were evaluated based on criteria such as energy consumption, specific power, mass-size efficiency, ease of maintenance, and safety. This comparative analysis (Table 1) informed the decision to select electric drives, particularly stepper motors, due to their superior performance in terms of precision, reliability, and cost-effectiveness.

Geometric and Load Calculations. Geometric parameters of the manipulator links were determined based on the GOST 30245-2003 standard. Load calculations were performed to estimate the mass and weight of each link, leading to precise torque requirements for the stepper motors.

Selection of Stepper Motors. Based on calculated load and torque values, suitable stepper motor models were selected from a standard range (Nema 16, 17, 23, 24) provided by Laser Components. The selection was made with a safety margin, ensuring reliable operation under varying conditions.

Integration of IoT and AI Algorithms. The system design incorporated cloud services and Internet of Things (IoT) connectivity, enabling the robotic system to interact dynamically with the vehicle. AI algorithms were used to adjust the manipulator to different vehicle models, ensuring precise positioning of the nozzle and optimal refueling operations.

Validation and Simulation. The proposed manipulator design and actuator selection were validated using simulation models, which allowed verification of mechanical and control system parameters before moving to hardware development.

This comprehensive methodology ensured the development of a robust and reliable robotic refueling system capable of precise, automated operation with minimal human intervention.

Results

This paper deals with the selection of suitable motors for the links of the designed manipulator.

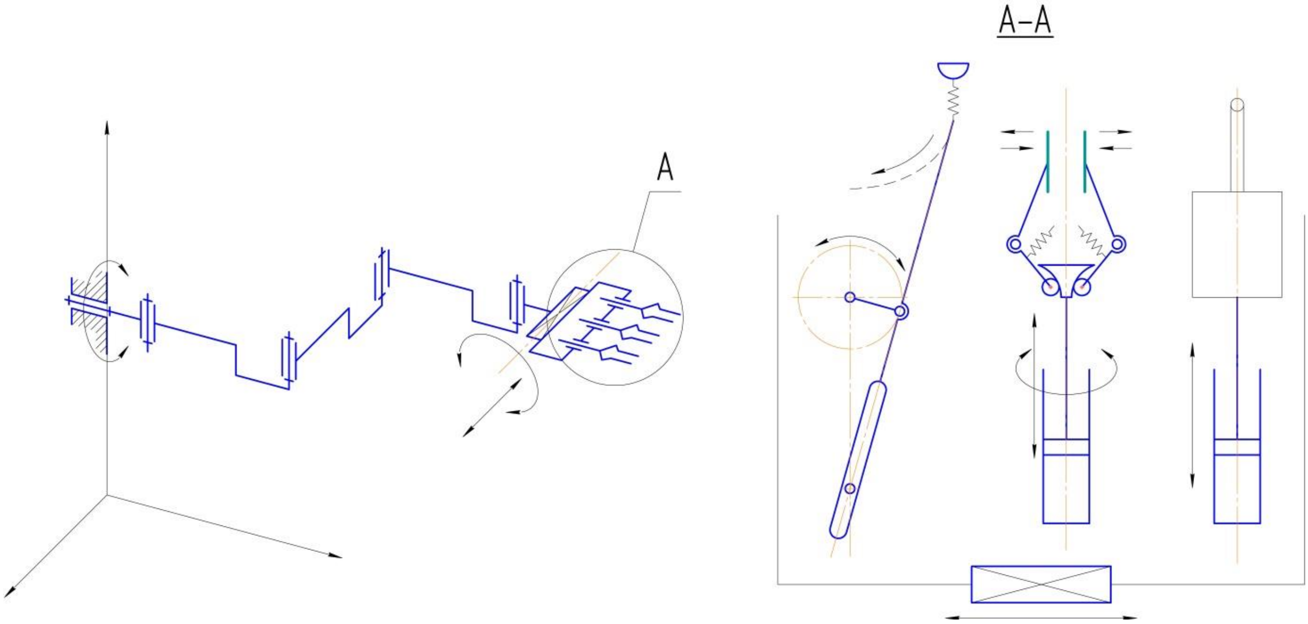
In order to provide coverage of the required working area, rotational motions in three planes are required. This requirement is due to the fact that for the designed robot-filler in the process of operation, to set the working panel is controlling the final position, depending on the design models of different vehicles, as well as a variety of types of operations: grabbing and opening the hatch cover; opening the fuel tank lid; feeding the gun into the neck, etc.

Next, to calculate the parameters of the robot manipulator in order to select the drive motors, let us represent the mechanism in the form of a spatial kinematic scheme.

The mechanical system of the refueling robot is a kinematic chain (Fig. 1, a) consisting of movable links with angular and translational displacements, allowing to move and set in a specifically defined spatial position of the drive of the working panel. The position of the working panel each time will be different depending on the make of the car, as well as at what angle and at what distance the car stood. The mechanisms of the working panel (Fig.1, b) allow using a special suction cup or hook to open the hatch, unscrew the plug, aim the filling gun with the tank, and perform the operation of fuel supply. At the end of refueling, the mechanism performs manipulations on removing the gun, screwing the plug, closing the hatch, and assembling the unit in its original position.

In order to realize the necessary movements, the mechanism must be equipped with a drive device that will allow the movement of links under the control of the program. The choice of the drive of the robot manipulator is an important task in the design, because it largely determines the structure, parameters and technological capabilities of the refueling robot as a whole [6, 7].

The main parameters of the drive are: power, speed, speed performance, accuracy of command signal processing. It is known that pneumatic, hydraulic, electric, and combined drives are distinguished by the type of energy carrier. For the final choice of the drive type, the authors carried out a comparative evaluation taking into account the drive weight, specific output power, efficiency, adequacy of energy sources of mechanical and control systems, the possibility of aggregate-modular construction, ease



a) robot manipulator; b) drive of the working panel

Figure 1. Kinematic diagram of the designed refueling robot [author's material]

of maintenance and operational safety. Comparative analysis of drives is presented in Table 1.

Table 1. Comparison of actuators by type of energy used

Criteria	Electric actuators	Hydraulic actuators	Pneumatic actuators
Energy supply costs	Low 1	High 3...5	High 7...10
Energy transfer	To an unlimited distance up to 300 km/s	At distances up to 100 meters	For distances up to 1000 m
Energy storage	Obstructed	Limited	Easily achievable
Linear movement	Difficult, expensive, low effort	Simple, high effort, good speed control	Simple, low effort, speed depends on the load
Rotational motion	Simple, high power	Simple, high torque, low frequency	Simple, low torque, high frequency
Operating speed of the actuator	Depends on the specific conditions	Up to 0.5 m/s	1.5 m/s and above
Efforts	High forces, no overloads allowed	Forces up to 3000 kN, overload protected	Forces up to 30 kN, overload protected
Positioning accuracy	+1 μm and above	Up to +1 μm	Up to 0.1 μm
Rigidity	High (mechanical intermediate elements are used)	High (hydraulic oils are virtually incompressible)	Low (air compressed)
Leaks	No	Create contaminants	No harm but loss of energy

Environmental influences	Insensitive to temperature changes	Sensitive to temperature changes, fire hazardous	Practically insensitive to temperature fluctuations, explosive

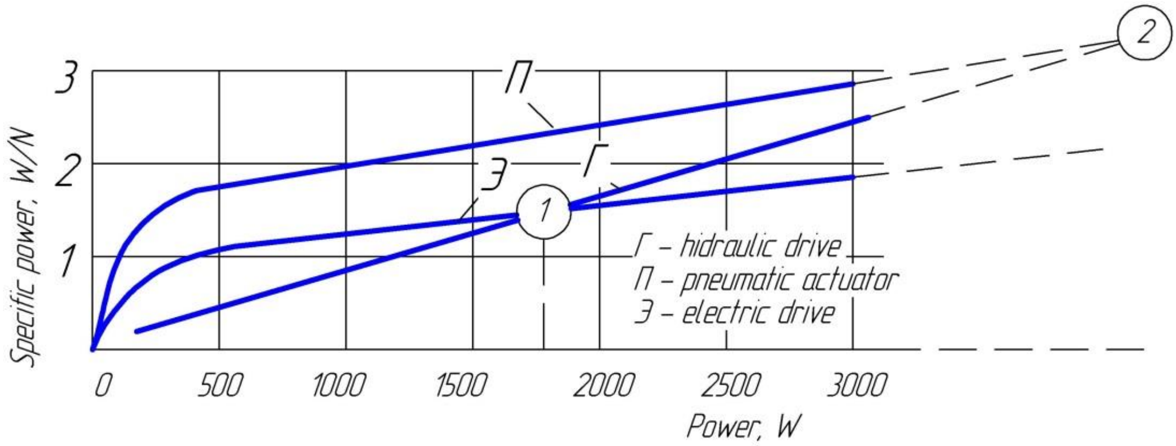


Figure 2. Specific power (related to weight) of different drive systems depending on absolute power [author's material]

Further the comparative characteristics of different types of drives by specific power are given [10]. When calculating the specific power of pneumatic actuators, the mass of air preparation equipment was taken into account, and that of hydraulic actuators - the hydraulic stations, which are included in the design of robots. The curves characterizing the mass-size efficiency of various drive systems used in mechatronic modules are shown in Fig. 2. Analyzing these dependencies, it is reasonable to note that at a power of more than 2 kW (after the intersection of characteristics in point 1), the mass-size efficiency of the electric drive becomes predominant. Point 2 indicates the intersection of characteristics of pneumatic and hydraulic drive. It can be tentatively concluded that for power values above 5 kW, the mass-size indices of the pneumatic actuator become preferable. In spite of the fact that the evaluation of such type is not complete for decision making on the choice of this or that drive system, as a basic preference is given to the electric drive [11].

Taking into account such factors as availability of energy carrier, ease of maintenance during operation, as well as based on the adopted layout solution, for this device is proposed to use electric stepper motors, which are a fairly accurate and inexpensive type of electric drive.

When choosing an electric drive, the authors give preference to stepper motors, due primarily to the reduction of design elements, and hence the reduction of the size of the structure. The following properties of stepper motors are the basis: the angle of rotation of the rotor is determined by the number of pulses that are applied to the motor; the motor provides full torque in stop mode; precision positioning and repeatability. Stepper motors allow rotor positioning with a precision of fractions of a degree, in addition, due to the peculiarity of their design, they have a huge lifetime and high reliability [8, 12].

Based on the configuration of the refueling robot, for each working link of the manipulator, it is necessary to select stepper motor models according to their characteristics and dimensions. According to the developed kinematic scheme, the manipulator has four main links, five articulations of the robot manipulator (Fig. 3). The drive of the working panel is not considered in this paper.

Kinematic dimensions of the links:

$$l_1 = 0{,}35 \text{ m};\ l_2 = 0{,}20 \text{ m};\ l_3 = 0{,}20 \text{ m};\ l_4 = 0{,}10 \text{ m};\ l_5 = 0{,}25 \text{ m}$$

According to the preliminary sketch layout of the mechanism, the geometric parameters of the refueling robot are determined. The bearing part of the lever has a profile of rectangular section, according to GOST 30245-2003 we choose the profile 100x50x3,0, then according to the assortment (Table 2):

Table 2. Assortment of rectangular profile according to GOST 30245-2003

h	b	t	Cross-sectional area	Reference values for axes						Weight of 1m, kg
mm				x - x			y - y			
			A, cm^2	I_x, cm^4	W_x, cm^3	i_x, cm	I_y, cm^4	W_y, cm^3	i_y, см	
100	50	3,0	8,41	106	21,3	3,56	36	14	2,07	6,60

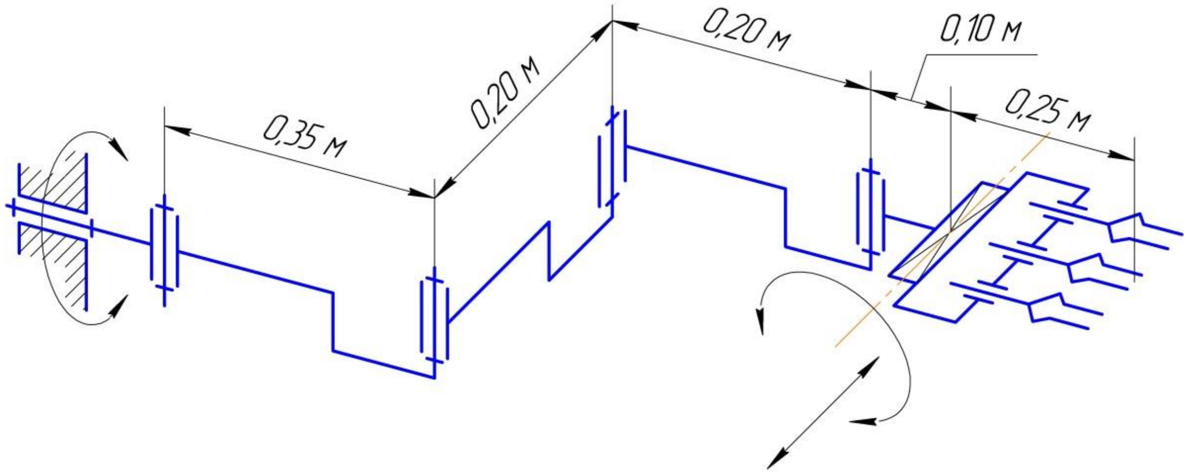


Figure 3. Geometric parameters of the robot manipulator [author's material]

Then the weight of each link:

$$G_i = G_{пог} \cdot l_i кг \quad (1)$$

$$G_1 = G_{пог} \cdot l_1 = 6{,}60 \cdot 0{,}35 = 2{,}31 \text{ kg};$$
$$G_2 = G_{пог} \cdot l_2 = 6{,}60 \cdot 0{,}20 = 1{,}32 \text{ kg};$$
$$G_3 = G_{пог} \cdot l_3 = 6{,}60 \cdot 0{,}20 = 1{,}32 \text{ kg};$$
$$G_4 = G_{пог} \cdot l_4 = 6{,}60 \cdot 0{,}10 = 0{,}66 \text{ kg}$$

The load capacity of the engine can be determined by the formula:

$$G_{дв\, i} = 1{,}3\left(\sum G_{i-4} + G_{РП}\right) kg \quad (2)$$

where $\sum G_{i-4}$ - is the weight of the lever mechanism of the robot manipulator, according to the kinematic scheme, kg;

$$\sum G_{1-4} = G_1 + G_2 + G_3 + G_4 = 2{,}31 + 1{,}32 + 1{,}32 + 0{,}66 = 5{,}61\text{kg};$$
$$\sum G_{2-4} = G_2 + G_3 + G_4 = 1{,}32 + 1{,}32 + 0{,}66 = 3{,}3\text{kg};$$
$$\sum G_{3-4} = G_3 + G_4 = 1{,}32 + 0{,}66 = 1{,}98\text{kg};$$
$$G_4 = 0{,}66\text{kg}$$

$G_{РП} = 16$- weight of the working panel drive, kg

1,3 - correction factor.

Then:

$$G_{дв\ 1} = 1{,}3(\sum G_{1-4} + G_{РП}) = 1{,}3(5{,}61 + 16) = 28{,}1 \text{ kg};$$
$$G_{дв\ 2} = 1{,}3(\sum G_{2-4} + G_{РП}) = 1{,}3(3{,}3 + 16) = 25{,}1 \text{ kg};$$
$$G_{дв\ 3} = 1{,}3(\sum G_{3-4} + G_{РП}) = 1{,}3(1{,}98 + 16) = 23{,}4 \text{ kg};$$
$$G_{дв\ 4} = 1{,}3(G_4 + G_{РП}) = 1{,}3(0{,}66 + 16) = 21{,}6 \text{ kg};$$
$$G_{дв\ 5} = 16 \text{ kg}$$

Required engine torque:

$$M_{Крдв\ i} = L_{i-5} \cdot G_{дв\ i}, \text{ N·m}$$

$$M_{Крдв\ 1} = L_{1-5} \cdot G_{дв\ 1} = 110 \cdot 28{,}1 \cdot 10^{-3} = 3{,}09 \text{ N·m};$$
$$M_{Крдв\ 2} = L_{2-5} \cdot G_{дв\ 2} = 75 \cdot 25{,}1 \cdot 10^{-3} = 1{,}88 \text{ N·m};$$
$$M_{Крдв\ 3} = L_{3-5} \cdot G_{дв\ 3} = 55 \cdot 23{,}4 \cdot 10^{-3} = 1{,}29 \text{ N·m};$$
$$M_{Крдв\ 5} = L_{4-5} \cdot G_{дв\ 4} = 35 \cdot 21{,}6 \cdot 10^{-3} = 0{,}75 \text{ N·m};$$
$$M_{Крдв\ 5} = L_5 \cdot G_{дв\ 4} = 25 \cdot 16{,}0 \cdot 10^{-3} = 0{,}4 \text{ N·m}$$

where L_{i-5} – is the length of the corresponding links of the manipulator, cm

From the standard range of hybrid stepper motors presented by Laser Components [9], taking into account the safety margin,we choose the Nema 16,17,23,24 motor (Fig.4,Table 3).

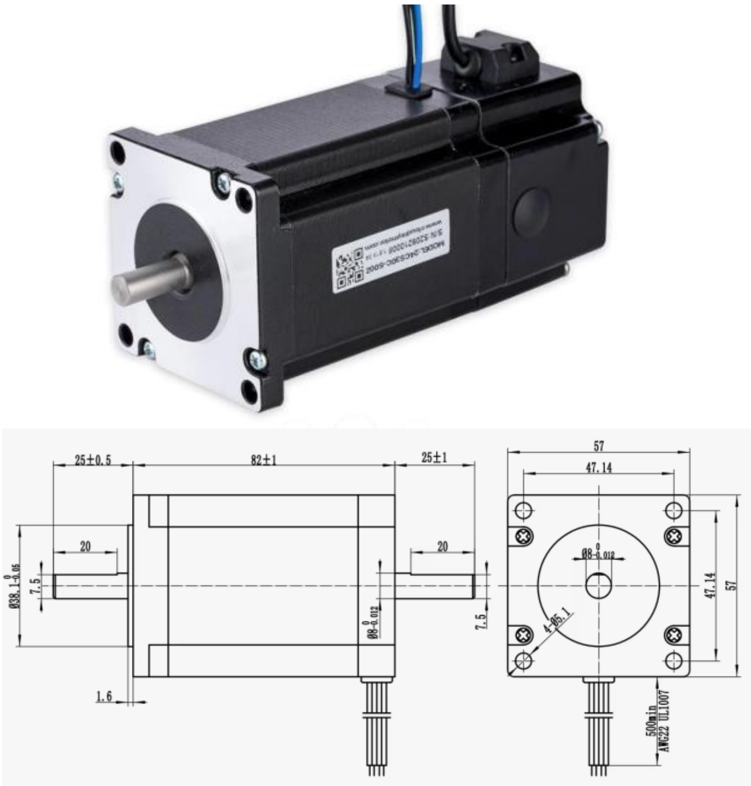


Figure 4. Stepper motor MS24HS5P4300-E Nema 24 [author's material]

Table 3. Technical parameters of stepper motor Nema 24, Nema 23, Nema 17, Nema 16

Model	Phase	Shaft	Length, mm	Rated current, A	Torque, Nm	Coil type
MS24HS5P4300-E	2	2	87	3	3,3	Bipolar
ML23HSAP4100	2	1	77	1	2,3	Bipolar

ML23HS8B4100	2	1	55	1	1,5	Bipolar
MS17HDBP4100	2	1	62,8	1	0,82	Bipolar
MS14HS5P4200-M	2	2	55	2	0,4	Bipolar

Discussion

The development and selection of actuators for the robotic refueling system demonstrated the critical role of system analysis, kinematic modeling, and comparative evaluation in designing a high-performance manipulator. The use of stepper motors as actuators was justified by their precision, reliability, and adaptability to varying operational conditions.

The analysis of different energy carriers (electric, hydraulic, pneumatic) revealed that electric drives, especially stepper motors, provide superior mass-size efficiency, positioning accuracy, and safety for robotic systems operating in environments with fluctuating temperatures and potential hazards.

The integration of IoT technologies and AI algorithms into the system architecture offers additional benefits, including enhanced adaptability to different vehicle models and real-time system monitoring. These technologies enable the robotic system to interact with vehicles seamlessly, ensuring safe and precise fuel delivery. The comparative analysis and simulation studies highlight that the stepper motor-driven manipulator can achieve accurate nozzle positioning, efficient fuel delivery, and minimal human intervention.

The study also addressed potential limitations such as the necessity for detailed calibration, the impact of vehicle placement variability, and the need for robust error-detection mechanisms to prevent operational failures. Future work should focus on integrating advanced sensors and improving the decision-making algorithms to enhance system autonomy and reliability further.

Conclusion

This research successfully developed a comprehensive approach for designing and selecting actuators for a robotic refueling system. Through systematic analysis, kinematic modeling, and comparative evaluation, electric stepper motors were identified as the optimal choice for ensuring precise, reliable, and cost-effective operation. The proposed system architecture integrates IoT technologies and AI algorithms to adapt dynamically to varying vehicle types and refueling scenarios, providing enhanced operational safety and efficiency.

The work lays a solid foundation for the next phases of development, which will include hardware prototyping, software development, and field testing. By addressing key challenges such as actuator selection, geometric modeling, and system integration, the study demonstrates the feasibility of creating a fully automated robotic refueling system that minimizes human involvement while ensuring safe and accurate fuel delivery. Future research will expand on these results by exploring more advanced control algorithms, sensor integration, and adaptive learning techniques to further improve system performance.

Conflict of interests. Correspondent the author states that there is no conflict of interest.

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