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The Pushing Mechanism Design of Jumping Robot

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Abstract. *In areas hazardous for humans, jumping robots serve as substitutes. They exhibit enhanced mobility when traversing uneven or rugged terrain, significantly broadening the application potential of mobile devices for territory surveillance, environmental monitoring after earthquakes, and other emergency situations where robot movement relies solely on jumping.*

Various design solutions for performing jumps are known, each with its own advantages, disadvantages, and implementation based on specific structural elements. To propel robots off the ground, different actuators can be used: spring-based mechanisms (with or without additional kinematic links), pneumatic or hydraulic systems, and those powered by fuel-air mixtures. Spring-based impact systems execute jumps by converting the potential energy stored in the spring into the kinetic energy of the robot's body.

The objective of the research is to justify the feasibility of developing cam mechanisms for jumping robots, taking into account the direction of their jumps in accordance with the distribution of forces and applied loads.

The methodology involved determining the impact force of the hammer in the cam mechanism under static loading. A calculation method for the parameters of the impact system was developed. Computer modeling of the spring compression phase using a lever device was conducted. The structural and technological parameters of the robot were substantiated, considering its mass, spring stiffness, impact system, and the cam profile, using Autodesk Inventor software. Calculations of forces, power, and design parameters of the impact system were presented, along with a detailed analysis of all phases of the jumping process. These phases include spring compression using a lever device, removal of the compression device, spring release, and the final ballistic phase (flight phase).

The methodology allowed for determining the design parameters of the cam mechanism based on specified kinematic and dynamic parameters of the jumping process.

Keywords: *jumping robot, cam mechanism, design, solid model, cam profile.*

Introduction

These days, mobile robots, which are complex mechatronic systems, have developed significantly. Initially, in the period from the 40s to the 70s years of the 20th century, their application areas were the military and space industries. Over time, more complex objects began to be created that can operate in conditions unacceptable for human life and existence, for example, in areas with radiation, where the radiation dose is several times higher than the permissible one.

One of the most promising areas of mobile robot development is jumping robots. The interest in robots that move off the surface is related to the fact that such objects have increased cross-country ability when moving over uneven or rough terrain, which significantly expands the possibilities of using mobile devices to monitor a certain area, monitor the environment after earthquakes and in other emergencies when robots can only move by jumping.

Review

The structures and mechanisms of movement of multi-link jumping robots are built by analogy with biological organisms that move by jumping, such as grasshoppers, frogs, and kangaroos. This method of movement is also realized by athletes in long jumps.

Among the methods of positioning before flight, the most common are turning the robot body on wheels or legs

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or changing the angle of the body to the surface by changing the position of its center of mass, as well as turning the acceleration module relative to the stationary body. After landing, jumping robots can be positioned to achieve a steady state from which the next jump can be realized by changing the geometry of the device's links or by changing the position of the center of mass. Another classification feature of jumping robots is the number of links included in them. There are two-, three-, and four-link robots. Various drives can be used to make robots off the surface, such as springs or with additional kinematic links, pneumatic, hydraulic, those that operate on a fuel-air mixture, and according to the type of movement performed by the links at the acceleration, pairs of rotational and translational motion are distinguished.

Jumping robots differ in weight, dimensions, jumping parameters and technologies, and methods of starting from the surface and landing on it. However, the task of designing a robot that performs a controlled jump with the required height and length remains actual, since in almost all created robots these parameters of jump are strictly related to the characteristics of the drives that are used to take objects off the surface.

In a significant number of robots, the jump is provided by a spring drive containing a spring compression mechanism [1]–[3]. The jump occurs when the potential energy accumulated in the spring is converted into the kinetic energy of the body.

The translational pair is formed by a mechanical transmission driven by a motor. This transmission compresses a spring located in the robot's leg. The energy accumulated in the spring is released when the motor is turned off, causing the robot to take off the surface. One of the possible variants of the drive is presented in [4]. It uses a cable wound around a drum to compress the spring. The drum is mounted in a body and driven by a motor through a bevel gear.

A remotely controlled jumping robot [5] is composed of a vibration unit and two compressed springs (Fig. 1). The vibration unit consists of two DC motors, two eccentric weights with a battery, and an electronic control system. Its main components are made of polycarbonate to ensure heat resistance.

The jumping mechanism of the TAUB robot provides a stable compression of the spring [6]. In MSU robots [7]–[10], the jump is provided by additional kinematic links. Different variants of kinematic linkage make it possible to provide different characteristics of the jumping process and various drive layouts (Fig. 2). In some designs, they are used to stabilize the robot during the flight stage.

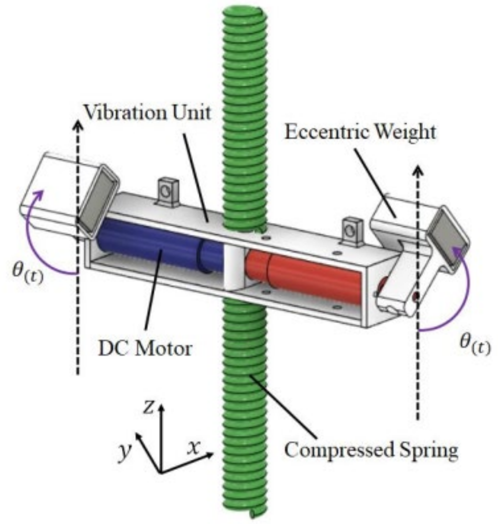

Fig. 1. Continuous jumping mechanism [5]

To enable jumping, pneumatic systems are used [11]–[19], but they are not sufficiently efficient due to the need for additional sealing and ensuring the direction of the jump (Fig. 3). Moreover, a special drive or compressor design is required to provide the impulse or impact action for the jump.

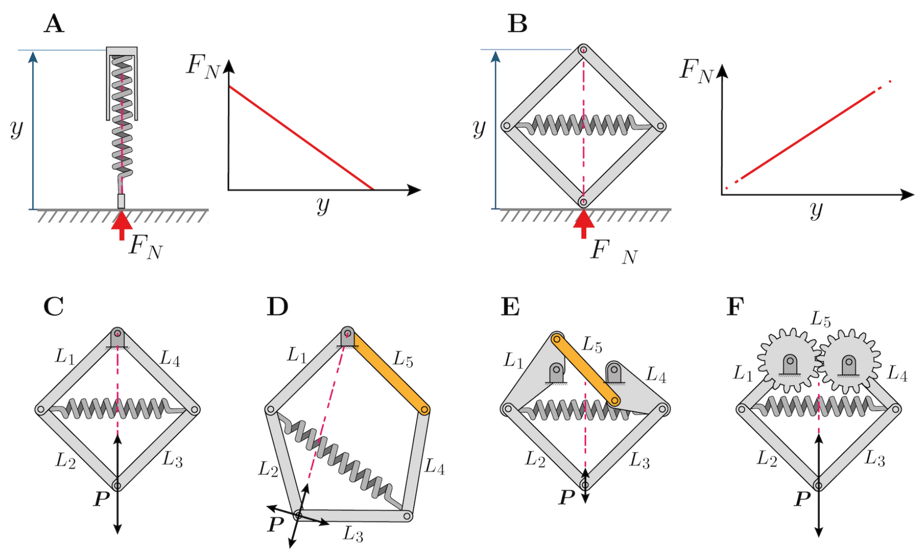

Fig. 2. The telescopic prismatic mechanism (*A*) and hinge rhomb linkage (*B*), with their characteristic ground reaction force with longitudinal displacement graph. From (*C–F*), synthesis of a synchronous hinge rhomb linkage using a pair of synchronizing gears. Dotted line extremes in graph B highlight singular or nonlinear behavior of FN depending on y for specific geometry configurations [10]

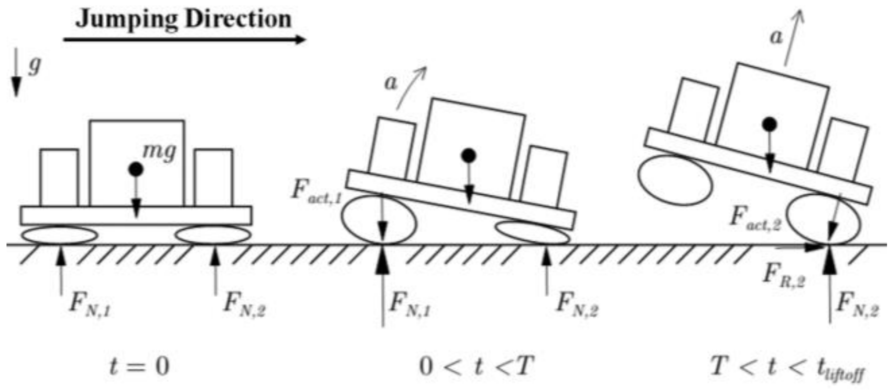

Fig. 3. Directional jumping concept [11]

In jumping robots, hydraulic actuators are used to enable the relative movement of links or compression of springs [20]–[22].

For reducing the weight of a jumping robot, the use of combustible fuels has been proposed, specifically propane (C_3H_8) as a flammable gas and nitrous oxide (N_2O) as an oxidizer [23]–[25]. Both gases are non-toxic, neutral, and stable, which makes them environmentally friendly.

The design of the hopping actuator is shown in Fig. 4. This actuator comprises a cylinder, an internal hollow piston, a magnet set, an ignition system, and some other components [25].

The hollow piston facilitates a compact design [25]. The fuel mixture enters the combustion chamber through the gas fuel inlets. The exhaust gas and air exit through the exhaust holes. The ignition process is initiated by a glow plug with a platinum filament, acting as a catalyst to accelerate the chemical reaction. The combustion process follows similar processes for internal combustion engines. A removable cylinder lid makes the actuator easy to assemble and maintain.

An actuator featuring two combustion chambers can be employed (Fig. 5). This design provides increased power, but it is also more complex.

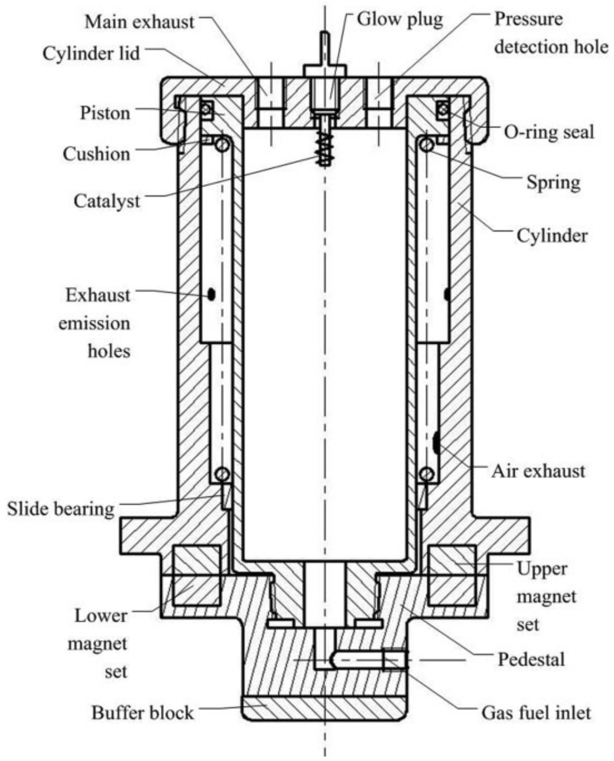

Fig. 4. Design of the hopping actuator [25]

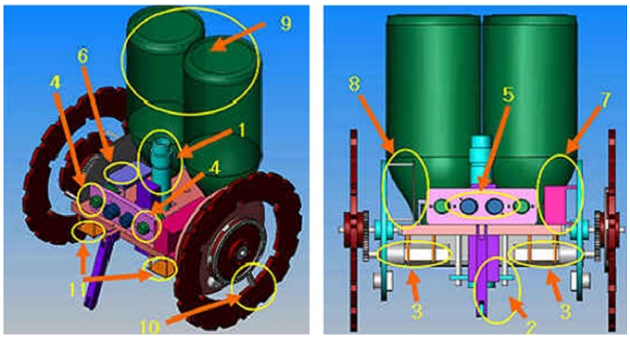

Fig. 5. Structure and components of the Scout Robot: *1*. cylinder, *2*. solenoid valve, *3*. motor encoder, *4*. camera, *5*. ultrasonic sensor, *6*. Bluetooth module, *7*. digital signal processor controller, *8*. electric power circuit, *9*. air tank, *10*. damper, *11*. motor driver [25]

An alternative to the impulsive (impact) movement of the leg is using a cam mechanism [26]. A properly selected cam allows for the effective execution of the jumping process (Fig. 6).

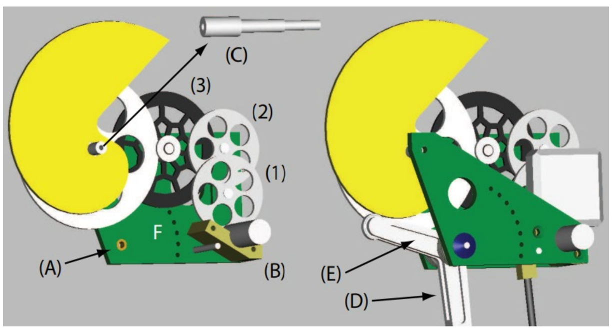

Fig. 6. CAD model of the gearbox. (A) brass bearing to reduce friction, (B) distance piece to align the two body plates, (C) cam axis, (D) slot in the main leg for the cam, (E) main leg, (F) series of holes for spring setting. (1), (2) 0.2 mm POM gears, and (3) 0.3 mm POM gears [26]

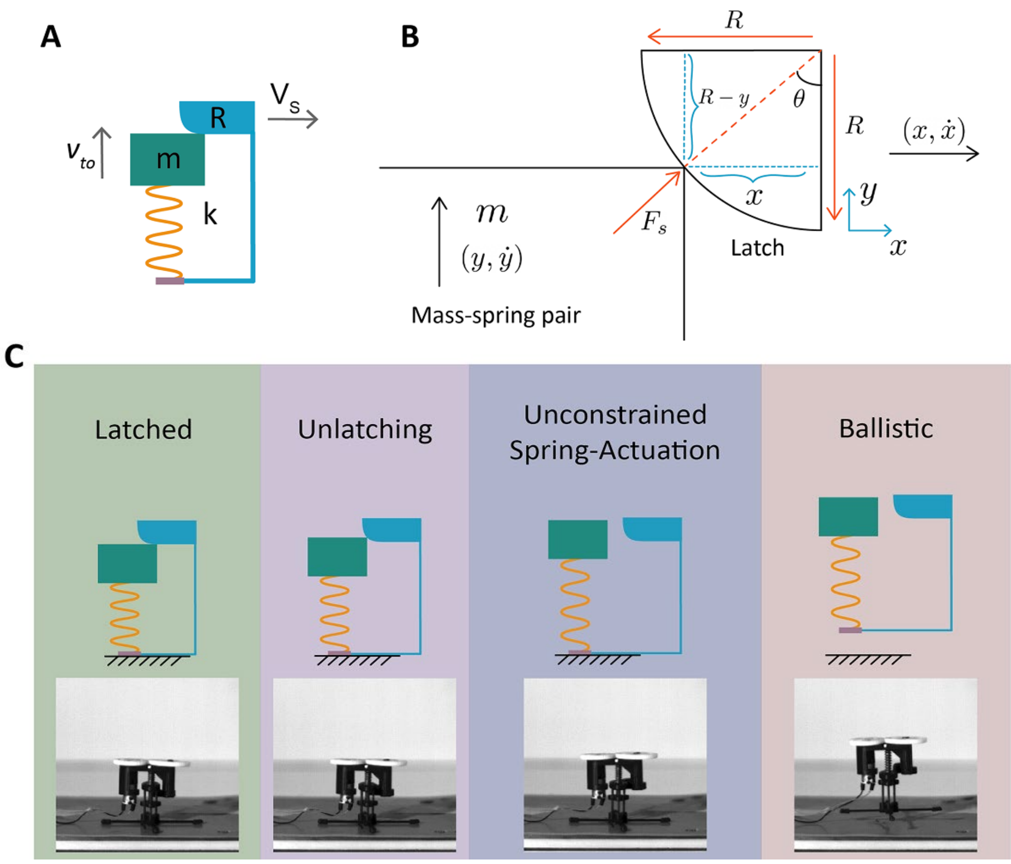

Fig. 7. (*A*) Reduced-order LaMSA model with the latch characterized by latch radius *R* and latch-motor actuation voltage VS. (*B*) Close-up view of the interface between the latch and mass-spring pair. Here, the constraint of constant latch velocity is relaxed, by allowing the latch retraction to be influenced by the feedback from the mass-spring pair. (*C*) Different LaMSA phases [27]

The jumping process consists of four phases: compression of the spring by the compression device (latched phase), removal of the compression device (phase of unlatching), the release of the spring (phase of unconstrained spring-actuation), and the flight stage (ballistic phase) (Fig. 7).

One of the variants of the compression device can be a cam-operated actuator. Its advantage is the combination of the compression and release devices in one part (cam), which allows for simplifying the design. A limitation may be the amount of spring deformation. It will affect the geometric dimensions of the cam, and, accordingly, the layout of the compression device. It is also necessary to consider the impact loads on the cam at the moment of spring release.

Main Part

A design of the jumping robot drive has been developed, shown in Fig. 8.

The jumping robot has three support legs. The jumping leg mechanism consists of a cam rotation drive (*1*), which compresses the compression spring (*3*) by rotating the cam (*2*). The compression spring is fixed in the cylinder (*4*). At the time of cam clicking (a jump transition at the cam profile), the energy stored in the spring propels the lever (*6*), connected to the slider (*5*) by a spring. The other end of the lever is connected to a leg (*9*), which is attached to it by a slider and moves along guides (*8*).

After the clicking, the energy from the spring is transferred through the lever to the leg, which, moving along the guides, gives the robot body an impulse to jump. After that, the jump takes place.

The robot's leg is positioned using two actuators: a leg rotation actuator relative to the foot (*7*) and a body rotation actuator relative to the leg (not shown in fig. 8).

The calculation of energy and structural parameters of the impact system was conducted considering the methodology [28].

Designing and manufacturing cam mechanisms is a complex and time-consuming process. The quality of the mechanism's operation depends on the accuracy of machining the cam's profile surface. An automated cam mechanism design system speeds up production time,

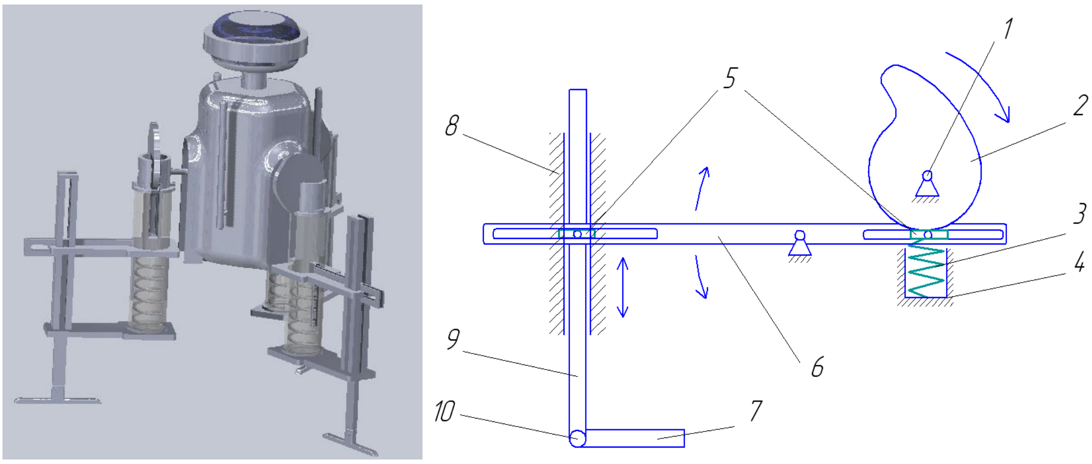

Fig. 8. Structure of the jumping robot: *1*. cam rotation drive, *2*. cam, *3*. compression spring, *4*. cylinder, *5*. slider, *6*. lever, *7*. foot, *8*. guides, *9*. leg

increases productivity and quality, allows for the creation of solid models of both individual parts and entire assemblies, facilitates assembly calculations, analyzes motion characteristics, examines the kinematic and dynamic characteristics of the cam mechanism, selects optimal mechanism parameters, and prevents errors at an early stage of design.

According to the proposed structure, the cam is the driving link, and the slider (pusher) is the actuating element (output link). The movement of the slider depending on the cam rotation angle is described by the following relationship:

$$x_2 = \phi_x(\phi), \tag{1}$$

where x_2 is the rectilinear motion of the slider when the cam is rotated by an angle ϕ.

During the retraction phase, the slider moves linearly along the guides under the action of the cam, and during the approach phase, it accelerates to a pre-impact speed due to the potential energy of the compressed spring. During the nearside dwell interval, the slider makes a strike (jump) followed by a dwell. A diagram of the cam phase angles is shown in Fig. 9.

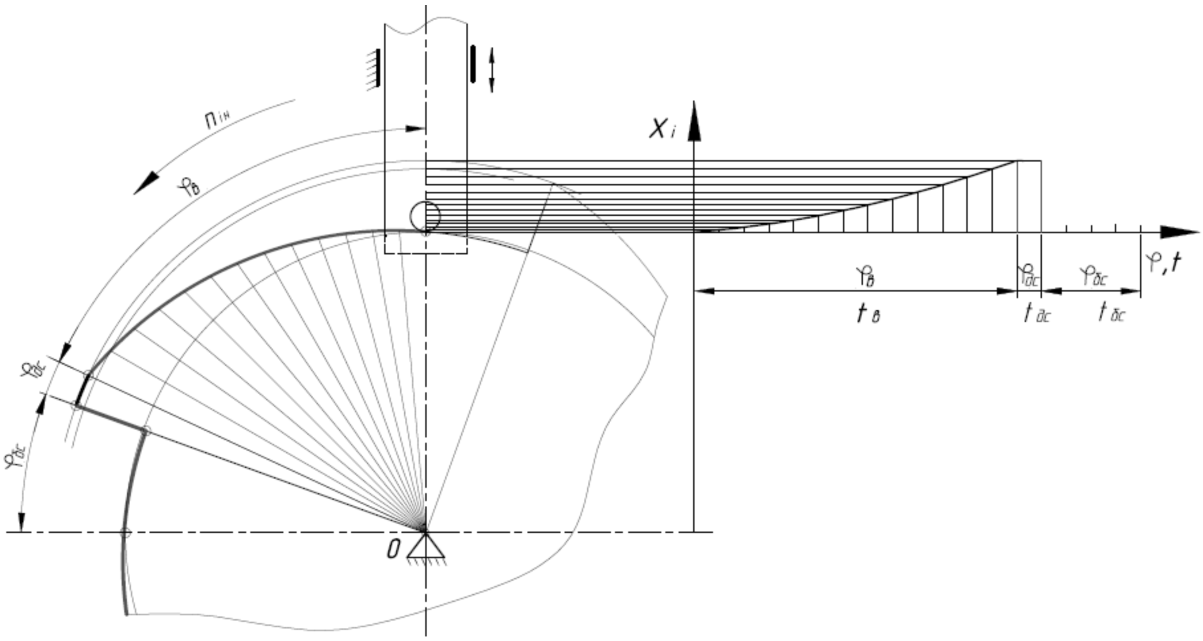

Fig. 9. The displacement diagram of the slider movement with the phase angles of the cam: 1 – cam; 2 – slider (pusher); $\boldsymbol{\phi_v}$ – retraction angle; $\boldsymbol{\phi_{ds}}$ – offside dwell angle; $\boldsymbol{\phi_{bs}}$ – nearside dwell angle

The working cycle of the slider movement can be divided into several intervals:

1) idle stroke $l_{is} = x_2$ corresponds to the retraction angle of the cam (slider moves to the extreme position (slider retraction) in time t_{zv};

2) The dwell period of the slider in the retracted state corresponds to the offside dwell angle of the cam t_{ds};

3) working stroke l_{ws} corresponds to the interval when the slider accelerates to the pre-impact speed (slider acceleration) t_p;

4) impact (jump) of the slider and transferring the impact force through the lever to the jumper's leg t_y;

5) dwell period of the slider after impact under the static load, that corresponds to the nearside dwell angle of the cam (impact - dwell) t_{bs}.

This way, the slider's working cycle can be written as:

$$T_C = t_{zv} + t_{ds} + t_p + t_y + t_{bs}, \quad (2)$$

The full cycle of the slider's movement (retraction, dwell, acceleration, impact, dwell) takes place in time:

$$T_C = 1/f, \quad (3)$$

where f is the frequency of impacts (jumps):

$$f = n{\cdot}z, \quad (4)$$

where n is the rotational speed of the cam, and z the number of cams.

The working process of the cam mechanism is represented by a diagram of the slider movements depending on the cam angle (fig. 9).

The main design parameters that determine the dimensions of the jumping mechanism are the geometric characteristics of its elements and the working stroke of the slider $l_p(x)$. The working stroke is determined based on the impact energy and pre-impact speed and is defined by the parameters of the cam.

Autodesk Inventor is a design environment that includes a system of specialized CAD documents (Documents), transient geometry (Transient Geometry), command manager (Command Manager), and user interface manager (User Interface Manager) [29]. Autodesk Inventor supports the following main types of documents: Assembly Documents, Part Documents, Presentation Documents, and Drawing Documents. Each type of document allows for the creation and manipulation of sets of component objects (Selection Set) and individual components (Component Definition). For each component, all the objects characterizing it and its properties are available.

For example, the description of a component (Component Definition) of a part (Part Document) includes sketches (2D and 3D contours), three-dimensional elements (extrusions, revolutions, sweeps, lofts, etc.) with reference sketches, construction elements (chamfers, joints, threads, etc.), functional elements (reference planes, axes, points), parameter tables controlling geometry. The description of a component (Component Definition) in an assembly document (Assembly Document) as an instance of a component (Component Occurrences) may include part document files (Part Document).

Elements of Transient Geometry are objects (points, vectors, matrices) that do not have graphical representation in models but are used in creating geometry in Autodesk Inventor documents.

Using objects of type Constraints in Assembly Documents establishes mutual constraints on the positioning and movement between parts, allowing for the creation of computer assemblies.

To construct a three-dimensional solid model, the coordinates of the practical cam profile are recorded in a file, which is then read and transmitted to Autodesk Inventor. Control of the modules is carried out using the Visual Basic.NET programming language. The problems regarding the transfer of information between different computer systems are solved based on this language.

The construction of the part begins with creating a two-dimensional sketch by calling functions written in VBA within the environment of Inventor. The purpose of these functions is to construct the cam profile as a sketch in Autodesk Inventor. It is highly convenient for further extrusion and other operations. The functions have initial input data such as the width, height, and hole radius. In Fig. 10, the solid model of the cam implemented programmatically in Autodesk Inventor is shown.

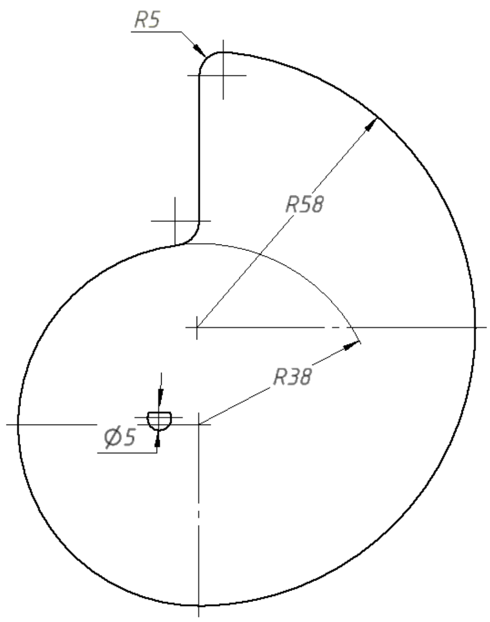

Fig. 10. 3D model of the drive cam (frontal view)

Similarly, subprograms were developed to create a sketch and a solid model of the pusher and other parts of the cam mechanism. At any stage of detail creation, it is possible to unfold it in real-time in a tinted mode and adjust the scale of the projected detail for better positioning. At

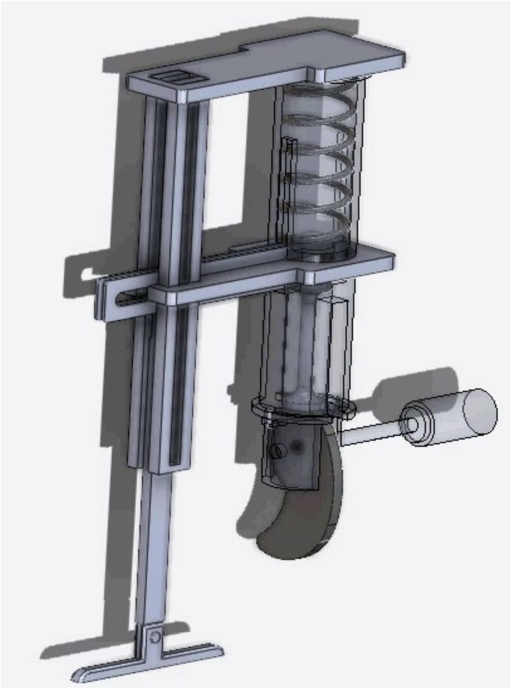

Fig. 11. Assembly of the cam mechanism in the Autodesk Inventor

the same time, the execution of the current editing command is not interrupted. Subsequently, with specially written functions, the computer assembly of the entire cam mechanism was programmatically carried out. Fig. 11 illustrates the programmatically obtained assembly of the cam mechanism in the Autodesk Inventor system.

Fig. 12. Experimental prototype of the cam mechanism

With Autodesk Inventor, the model is treated as a real mechanism: when moving certain parts, their interaction with the environment is controlled. If any part is fully fixed or deprived of all degrees of freedom, then upon contact with it, the mechanism will stop, reflecting real problems in the operation of the finished product.

Such a system of automated cam mechanism design speeds up design processes and conducts various types of calculations, simulation modeling, and three-dimensional motion animation. The system links drawing views with initial models, so any changes made to the models are automatically reflected in the drawings for subsequent manufacturing on CNC machines or 3D printers. Continuous graphical representation of results and real interactivity further enhance efficiency. The built-in multi-page printing manager in Autodesk Inventor automatically arranges the set of drawing sheets to fit the appropriate paper size and optimizes the print file. Printing output is done directly on a plotter or through a print file.
To obtain more illustrative results and to verify the accuracy of the analytical dependencies for calculating the parameters of the jumping robot, it is designed the cam mechanism in the solid modeling environment of Autodesk Inventor. Additionally, the cam mechanism is reproduced by using 3D printing to verify the adequacy of the assumptions made (Fig. 12).

Conclusions

One of the most promising areas of mobile robot development is jumping robots. Jumping, as a method of movement, offers many advantages, as it represents an intermediate step between moving directly on a supporting surface and flying.

Various mechanisms can be used to propel robots off the surface, for example, with springs or with additional kinematic links, pneumatic or hydraulic systems, and those powered by a fuel-air mixture.

A jumping device using a cam mechanism combines compression and release elements into one component (cam).

Using the Autodesk Inventor software environment, the cam mechanism has been designed, significantly enhancing the efficiency of the design process and enabling the investigation of various operating modes of the device according to the established requirements.

Creating the prototype of the cam mechanism using 3D printing allows for a more thorough exploration of the jumping mechanism by the parameters of the cam profile, ensuring the necessary height of the robot's jump.

Autodesk Inventor enables speeding up the design process, performing various types of calculations, simulation modeling, and creating three-dimensional animations of the movement of cam mechanisms and the jumping drives as a whole.

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Проектування штовхаючого механізму стрибаючого робота

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Анотація. *В територіях, небезпечних для людини її заміною є застосування стрибаючих роботів. Вони мають підвищену прохідність при русі по нерівній або пересіченій місцевості, що істотно розширює можливості застосування мобільних пристроїв для нагляду за певною територією, моніторингу довкілля після землетрусів і в інших надзвичайних ситуаціях, коли переміщення роботів можливе лише з використанням стрибків.*
Відомі різні конструктивні рішення щодо здійснення стрибка. Але кожен варіант має свої переваги та недоліки, а також реалізацію на основі констрктивних елемнетів. Для відриву роботів від поверхні можуть використовуватися різні приводи: пружинні або з додатковими кінематичними ланками, пневматичні, гідравлічні, такі, що працюють на паливно-повітряній суміші. Пружинні ударні систем реалізують стрибок шляхом перетворення закумульованої в пружині потенційна енергії в кінетичну енергію корпусу.
Метою дослідження є обгрунтовання доцільність розробки кулачкових механізмів для стрибаючих роботів із врахуванням напряму їхнього стрибка відповідно до розподілу сил і прикладених навантажень.
Використовувалася методика визначення ударного зусилля бойка кулачкового механізму з статичним навантаженням бойка. Розроблено методику розрахунку параметрів ударної системи. Проведено комп’ютерне моделювання фази стиснення пружини важільним пристроєм. Конструктивні та технологічні параметри робота обгрунтовано з урахуванням його маси, жорсткості пружини, ударної системи, а також профільної поверхні кулачка за допомогою середовища Autodesk Inventor. Представлено розрахунок сил, потужності та конструктивних параметрів ударної системи, а також детально проаналізовано всі етапи процесу стрибка. Ці етапи включають стиснення пружини важільним пристроєм, видалення стискуючого пристрою, вивільнення пружини та фінальну балістичну фазу (фазу польоту).
Методика дозволила на основі заданих кінематичних і динамічних параметрів процесу стрибка визначити конструктивні параметри кулачкового механізму кулачкового механізму.

Ключові слова: *стрибаючий робот, кулачковий механізм, твердотільна модель, профіль кулачка.*