Hydraulically Driven Unit Converting Rotational Motion into Linear One

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Abstract The contribution concerns a unit which can be implemented in driving hand prostheses, surgical manipulators and other equipment, the operation of which is based on linear motion. The state-of-the-art research presents several medical devices usually driven by means of electric or hydraulic, complex elements. The primary purpose of this work is to provide a solution that, due to simplicity of its design, will be an alternative to existing expensive devices. Simultaneously, the goal of the efforts is to ensure high precision and repeatability of linear movement. The proposed device comprises two hydraulic actuators driven by a stepper motor. Apart from presenting the design of the unit, the following work comprises description of modelling of the unit operation supplemented with presentation of the constructed prototype and results of initial experimental evaluation. Eventually, conclusions are drawn, pointing several amendments which are recommended for implementation in the future work.

1 Introduction

Extremity and limb amputations have been known to humans for centuries. Archaeological findings show that people have been trying to replace missing parts of their bodies with artificial substitutes already in the Ancient Egypt [1]. Despite many ages that have passed accompanied by development of technology, still, replacing the lost body part with an artificial one, being able to resemble natural functioning, is one of the most challenging aspects in the field of rehabilitation and prosthetic technology.

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Many attempts have been made throughout years to solve the abovementioned problem and mimic the movement of, for instance, a human hand, the prosthesis of which will be the concern of this work.

Prosthetic extremities are met in a variety of forms and applied technologies. The simplest designs are purely cosmetic and are used to mimic the shape of the missing hand. However, one of the biggest needs of amputees is to have the functioning of their extremities resembled to the possibly greatest extent. This is the reason that led to many efforts aimed at creating prostheses allowing to perform movements in a manner similar to the one of the natural hand. Most of hand prostheses are comprised of body-powered devices, including hooks or multi-fingered devices employing cables to manipulate their elements. The patient is supposed to wear a dedicated harness and manipulate the hand by means of moving the opposite shoulder. However, due to unsatisfactory and uncomfortable operation of such units, the improvement in the field of extremity prosthetics is one of the topics which is still under investigation.

The breakthrough in the design of such devices may be hard to achieve, since, as mentioned in [2], only few major enhancements have been observed since the early 1960s. Employment of external power was one of the hand prosthesis improvements which aimed at aiding the body-powered device. One of the examples of artificial hands is the Utah-MIT hand, being the robotic, four-fingered end effector powered pneumatically and using tendon-like cables [3]. Tendons have been also employed in the Salisbury hand [4], where they have been supplemented with electric drive motors as well as potentiometers and accelerometers to manipulate three fingers. Another example can be the BarrettHand [5]. All the aforementioned devices were capable of grasping and other manipulatory tasks, however, their operation was still far from the one of a human extremity. Among modern devices, the one referred to as the IOWA hand should be mentioned, the fingers of which are spring-like. The hand has been described in [2]. Special attention should be paid to the HANDLE project [6] conducted by researchers from the European Union. The project has resulted in a device being equipped with a number of sensors, including pressure sensors, and elements of artificial intelligence. The hand not only mimics movements of a human extremity, but also resembles its appearance. Modern prostheses comprise also hydraulic devices. Fluidhand [7] and i-limb [8] are hydraulically driven hand prostheses resembling both the appearance and functionality (manoeuvrability) of a human extremity to a large extent. i-limb has been successfully introduced onto the market by Touch Bionics Inc. Another interesting design of a hydraulic prosthesis, the Delft Cylinder Hand, has been proposed by Delft University of Technology [9]. The prosthesis is claimed to be about 50 % lighter than corresponding electrical instruments.

The aforementioned hydraulic devices are a competitive alternative for electric and, undisputedly, also for cosmetic prostheses. However, other solutions should be still taken into consideration in order to develop devices of simpler (less complex) and thus less expensive design. Development of the device fulfilling the aforementioned requirements is the goal of our efforts.

The solution presented in this work is intended to be introduced also into surgical manipulators, since the demand for such specialistic devices is constantly growing. Both the surgical manipulators and their drive units must be sufficiently tight and resistant to corrosion. They must be made of materials (e.g., surgical steel) that do not negatively influence living organisms. High precision is necessary while constructing devices which are intended to get into contact with an organism, since lack of tightness may lead to leakage of body fluids to the inside of a device, and vice versa.

To drive medical equipment, such as the abovementioned manipulators, the operation of which is based on linear motion, electric actuators are usually used. However, their main disadvantage is, as in the case of electrically driven hand prostheses, complex design accompanied by the fact that the drive unit cannot be placed in close vicinity of the piston executing the linear movement. Thus, the drive unit has to be located at a distance from the surgical site and be connected to the piston by means of special rods and tension members. As a result, the range of motion that can be achieved by the device is limited.

Apart from the above mentioned applications, the design presented in this work can be also implemented in other devices that require precise movement and stiffness accompanied by reproducibility of performed linear motion.

The presented paper comprises supplementary information basing on the former work [10].

2 The Idea

The proposed unit converting rotational motion into linear motion is chosen to be hydraulically driven, since the authors claim that such a solution is favourable over typical electric drives. In hydraulic actuators, the drive unit is used only to produce pressure and to force the fluid flow through the tube to other parts of the device. In such a way, it can be separated from the end actuator, what is desired in the case of both hand prostheses and surgical manipulators. Furthermore, elements of the unit are connected with each other by means of elastic tubes, what ensures greater range of motion than in the case of electrically driven devices and possibility of reaching hardly accessible locations. If small enough, tubes can be placed inside patient's body.

The idea implemented in the unit is to use a stepper motor connected to a driving actuator which, in turn, is linked with an executing actuator by means of an elastic tube. As a result of rotational motion of the stepper motor's rotor, hydraulic fluid is pushed through the driving actuator and further, through the tube, in a linear manner causing linear motion in the executing actuator.

Two propositions of the unit design have been provided. In the first concept (see Fig. 1a), the stepper motor is intended to be fixed to the foundation. An internally threaded piston is incorporated inside the driving actuator while the shaft connected to the stepper motor has an external thread. The shaft screws the piston into the

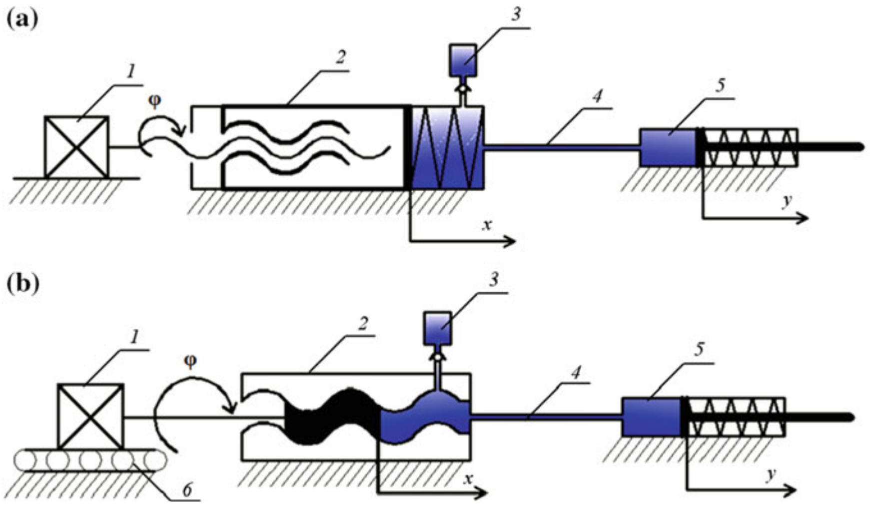

Fig. 1 Conceptual drawings of the unit: **a** variant with fixed stepper motor, **b** variant including a roller guideway. *1* stepper motor, *2* driving actuator, *3* compensation container, *4* hydraulic tube, *5* executing actuator, *6* roller guideway, φ rotation of the stepper motor shaft, x, y position of the actuators [10]

actuator and the pressure generated by the moving piston causes the fluid to flow out of the actuator, inducing in this manner motion in the executing actuator. Both actuators are single acting, i.e. they are comprised of springs, the role of which is to facilitate backwards motion of the pistons during their withdrawal from the actuators.

The second concept (see Fig. 1b) assumes having the stepper motor placed on a linear type roller guideway. Due to implementation of such solution, the drag of the stepper motor is reduced and its movement is possible. The design of the driving actuator is simplified in comparison to the first concept. The spring is removed, and so is the piston. The role of the latter is taken by the motor's shaft which, in this variant, is ended with an element the shape of which corresponds to the internal thread of the actuator. In this manner, the element connecting the motor and the actuator is a shaft and a piston at the same time. In addition, both concepts comprise the presence of a compensation container. Due to improved simplicity of design, the second concept has been chosen for further investigations.

Elements presented in Fig. 1 are supplemented with a power supply and a controller of the stepper motor. In addition, a metal bellow is located at the interface between the stepper motor and the driving actuator in order to create a proper connection between the shaft and the piston.

3 Modelling

As the concept of the unit has been chosen, its behaviour could have been also modelled. For this purpose, mathematical as well as simulation models have been developed and, on their basis, an analysis has been conducted.

First of all, a model comprising all necessary physical variables has been created as shown in Fig. 2.

In Fig. 2 x and y indicate linear motion of actuators; p_1 and p_2 stand for pressure of the hydraulic fluid inside the driving actuator and the executing actuator, respectively; V_{10} and V_{20} describe initial volumes of the actuators; E is the bulk modulus of the hydraulic fluid; S_1 describes the area of the piston of the driving actuator; S_2 and m_2 stand for area and mass of the piston of the executing actuator, respectively; c_2 and α represent viscous damping coefficient and Coulomb damping ratio between the piston and the cylinder of the executing actuator, respectively; k describes capacity of the hydraulic tube, k_2—stiffness of the spring inside the executing actuator, while F indicates external force.

In the next step of modelling, a mathematical model of the unit has been created, consisting of three differential Eq. (1), based on the information provided in Fig. 2. Two of these equations are related to the hydraulic balance in the system, i.e. the first equation of (1) describes the output of the driving actuator while the second represents the input to the executing actuator. The last equation of (1) gives information concerning the force balance in the second actuator.

$$\begin{gathered}\left(\frac{V_{10}}{E}-\frac{S_1}{E}x\right)\dot{p}_1=S_1\dot{x}+k(p_1-p_2),\\ \left(\frac{V_{20}}{E}+\frac{S_2}{E}y\right)\dot{p}_2=-S_2\dot{y}+k(p_1-p_2),\\ m_2\,\ddot{y}+c_2\dot{y}+k_2y=S_2p_2-\alpha S_2p_2\operatorname{sgn}\dot{y}-F,\end{gathered}\tag{1}$$

where meaning of the symbols follows the description provided below Fig. 2.

Having the mathematical model, a simulation model could have been developed. For this purpose, Matlab Simulink environment has been employed.

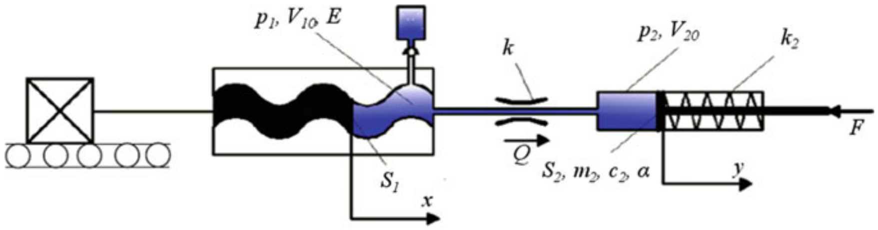

Fig. 2 Physical variables describing the considered unit [10]

The simulation has been performed for the first second of operation of the unit ($\tau = 1$ s). Velocity of the first actuator ($\dot{x}$) has been used as an exciting factor having the most significant influence on the mathematical model. It has been chosen as a sinusoidal signal $\dot{x} = 0.01 + 0.005 \sin(1000\, t)$ m/s. The areas of both pistons and initial volumes of the actuators have been chosen to be identical ($S_1 = S_2 = 201 \times 10^{-6}$ m^2, $V_{10} = V_{20} = 7.6 \times 10^{-12}$ m^3) in simulations in order to illustrate simultaneous operation of the actuators in a more convenient way. Capacity of the tube has been found with the employment of the Hagen–Poiseuille equation and equals to 7.9×10^{-12} m^4 s/kg. Other fixed parameters are: $m_2 = 0.03$ kg, $c_2 = 117.3$ N s/m, $k_2 = 195$ N/m, $E = 1.4 \times 10^9$ Pa, $\alpha = 0.1$. External force acting on the executing actuator $F = 10$ N. Simulation results are depicted in Figs. 3, 4, 5, 6 and 7.

What should be emphasized, an assumption regarding the driving actuator has been made while creating the mathematical model, i.e. resistance of the piston and the guideway against motion is assumed to be compensated by appropriate power of the stepper motor.

The difference between pistons position at the end of the simulation is at the level of c.a. 0.03 mm, as shown in Fig. 4. Such a value can be treated as almost negligible and stands for good correlation between actuators movement.

Figure 5 indicates that velocity of the piston of the executing actuator undergoes rapid changes in the initial part of the simulation (close-up of this part of the plot can be found in Fig. 6) and when external load F is applied. However, the curve reaches its final, stable trajectory within less than 0.005 s. Velocities are shifted in phase by 0.001 s.

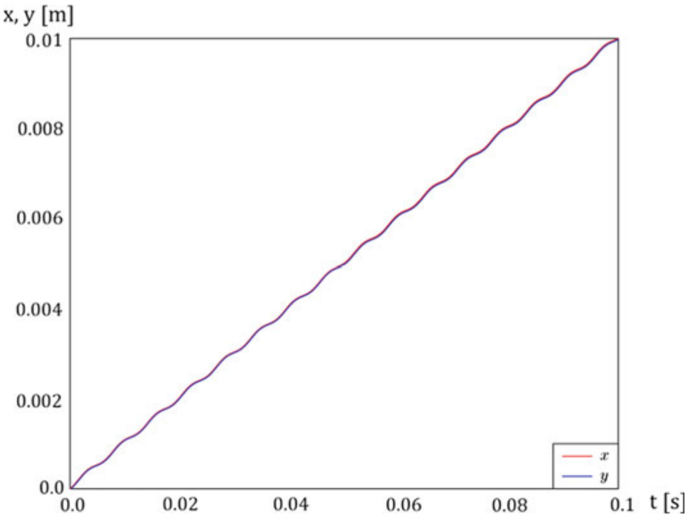

Fig. 3 Time versus position of the driving actuator piston (x) and the executing actuator piston (y)

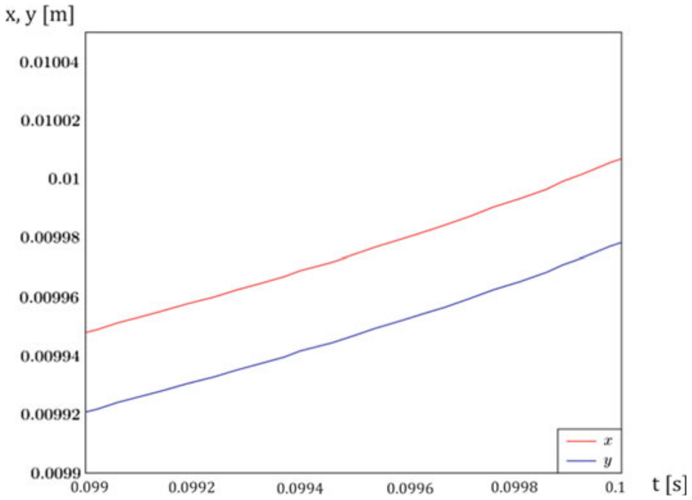

Fig. 4 Time versus position of the driving actuator piston (x) and the executing actuator piston (y) in the final part of the simulation

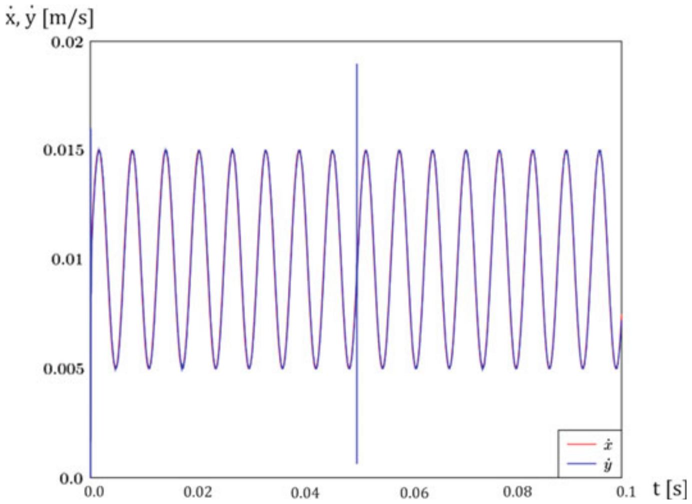

Fig. 5 Time versus velocity of the driving actuator piston ($\dot{x}$) and the executing actuator piston ($\dot{y}$)

As it can be noticed by looking at Fig. 7, pressure in the first actuator is higher than the one in the second actuator. Rapid increase in pressure is observed twice, i.e. when the driving actuator begins to operate and when the external load F is applied. In the latter case, pressure inside the unit raises by 0.3 MPa. Thus, velocity of the piston of the second actuator can be stabilised.

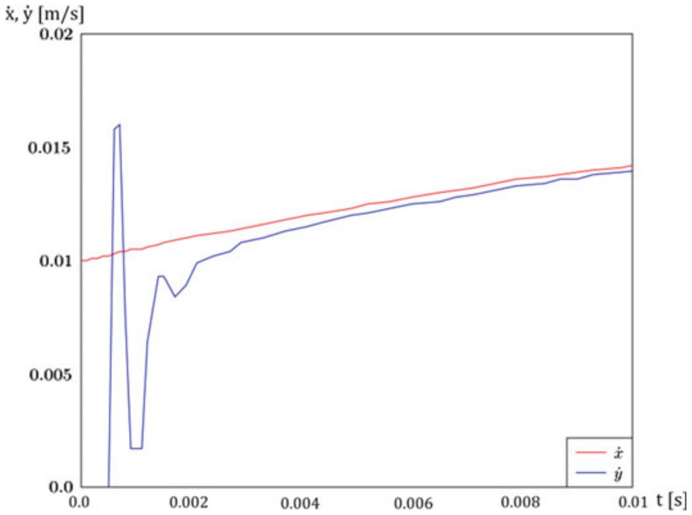

Fig. 6 Time versus velocity of the driving actuator piston ($\dot{x}$) and the executing actuator piston ($\dot{y}$) in the initial part of the simulation (0.01 s)

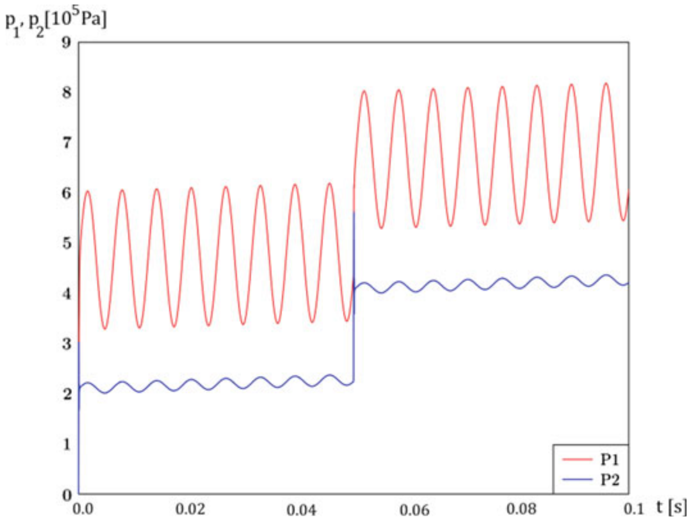

Fig. 7 Time versus pressure of the hydraulic fluid inside the driving actuator piston (p_1) and the executing actuator piston (p_2)

Furthermore, for the purpose of future analysis, transformation of Eq. (1) can be conducted in a manner as follows. Assuming dimensionless: time $\tau = t/\sqrt{\frac{m_2}{k_2}}$, positions $X = \frac{S_1}{V_{10}}x$, $Y = \frac{S_1}{V_{10}}y$, and pressures $P_1 = \frac{p_1}{E}$, $P_2 = \frac{p_2}{E}$ as well as dimensionless parameters: $\beta = \frac{S_2 V_{10}}{S_1 V_{20}}$, $a_1 = \sqrt{\frac{m_2}{k_2}} \frac{kE}{V_{10}}$, $a_2 = \sqrt{\frac{m_2}{k_2}} \frac{kE}{V_{20}}$, $d = c_2 \sqrt{\frac{1}{m_2 k_2}}$, $g = \frac{S_1 S_2 E}{k_2 V_{10}}$, α (as given before) and functions: $\mathrm{sgn}\left(\frac{V_{10}}{S_1}\sqrt{\frac{m_2}{k_2}}\dot{Y}\right) = \mathrm{Sgn}\dot{Y}$, $\frac{S_1}{k_2 V_{10}} F_2\left(\sqrt{\frac{m_2}{k_2}}\tau\right) = f(\tau)$, the counterpart dimensionless form of Eq. (1) is as follows:

$$
\begin{aligned}
(1 - X)\dot{P}_1 &= \dot{X} + a_1(P_1 - P_2), \\
(1 + \beta Y)\dot{P}_2 &= -\beta\dot{Y} + a_2(P_1 - P_2), \\
\ddot{Y} + d\dot{Y} + Y &= gP_2 - \alpha g P_2 \mathrm{Sgn}\dot{Y} - f_2(\tau).
\end{aligned} \tag{2}
$$

Eventually, the system depending on 10 parameters is reduced to the one depending on only 6 parameters. In both dimensional and dimensionless forms one function is also present, i.e. $F(t)$ and $f(\tau)$, respectively.

4 The Prototype

To study real behaviour of the developed unit converting rotational motion into linear one and compare the results with the outcome of modelling, a prototype has been created. For this purpose, a driving actuator has been manufactured according to the drawing depicted in Fig. 8 and connected to a ready-made hydraulic executive actuator.

The actuator can be tested in two variants, i.e. in the configuration shown in the above figure, corresponding to the concept being under consideration as well as in the configuration supplemented with additional elements used to provide better sealing of the actuator (see Fig. 9). In the first variant the sealing is assumed to result from tight fit of threads of both the piston and the cylinder.

As far as the configuration presented in Fig. 9 is considered, the principle of its operation is as follows. Motion of the threaded piston into the cylinder induces

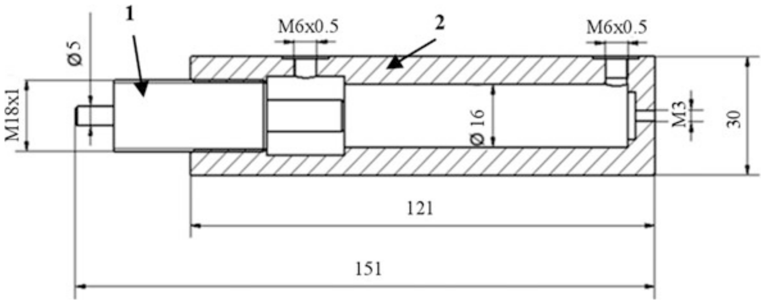

Fig. 8 Schematic diagram of the driving actuator. *1* Piston, *2* cylinder [10]

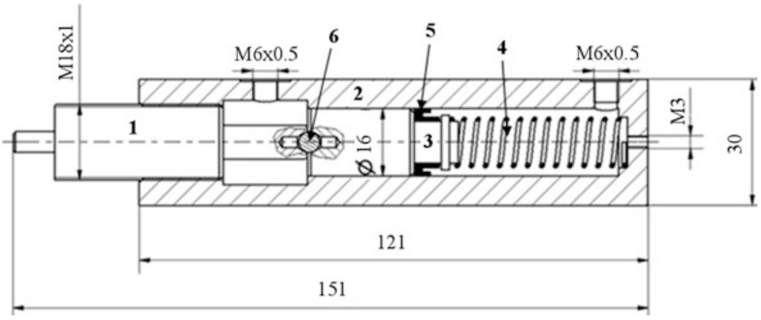

Fig. 9 Schematic diagram of the driving actuator in the second configuration. *1* Threaded piston, *2* cylinder, *3* intermediate piston, *4* spring, *5* seal, *6* metal ball [10]

motion of the intermediate piston which accompanied by a lip seal (or, in other words, radial shaft seal). The spring facilitates backwards motion of the intermediate piston during its withdrawal while the role of the metal ball is to reduce friction between pistons. The cylinder is manufactured of bronze due to low ratio of friction between the bronze cylinder and steel pistons. The prototype of the unit, including the abovementioned actuator, is shown in Fig. 10.

Experiments conducted with the use of both configurations of the driving actuator have shown that the first variant (Fig. 8) does not provide satisfactory fit of the internal thread of the cylinder and the external thread of the piston. As a result, hydraulic oil has leaked out of the actuator, what is the reason why further functional tests have been conducted for the configuration comprising additional internal elements (Fig. 9).

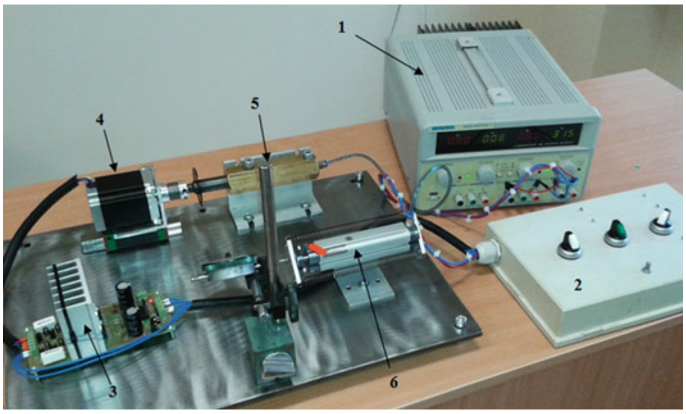

Fig. 10 The prototype of the hydraulic unit converting rotational motion into linear one. *1* Power supply, *2* stepper motor control panel, *3* driver of the stepper motor, *4* stepper motor on a roller guideway, *5* driving actuator, *6* executing actuator [10]

5 Testing

5.1 Unit Precision Test

To test the precision of conversion of rotational motion into linear one a scale wheel has been mounted to the shaft linking the stepper motor with the driving actuator (or, in other words, to the threaded piston of the driving actuator), see Fig. 11. In addition, a dial gauge has been installed on the surface of the piston of the executing actuator. Investigation of rotation of the scale wheel was facilitated by means of video capture and checking the recording frame by frame.

Conducted tests have shown that, for 1 mm thread pitch of the piston, one rotation of the stepper motor's rotor corresponds to the displacement of the executive actuator piston by 1 mm. The difference between positions of actuators has not exceeded 0.03 mm, what coincides with the results of numerical simulation.

5.2 Stiffness Test

Stiffness of the developed unit has been tested by means of applying external load to the piston of the executing actuator and measuring response of the unit with the use of a dynamometer. To measure displacement of the piston the dial gauge has been employed.

Response of the piston to the load of 10 N was equal to 0.01 m. Further increase in the acting force by 10 N has resulted in displacement of the piston by another 0.01 m. On the basis of these results the stiffness of the unit has been found which equals to $k = 1 \times 10^6 \left(\frac{\mathrm{N}}{\mathrm{m}}\right)$.

Apart from the conducted tests, further evaluation regarding response of the device to different load is supposed to be conducted.

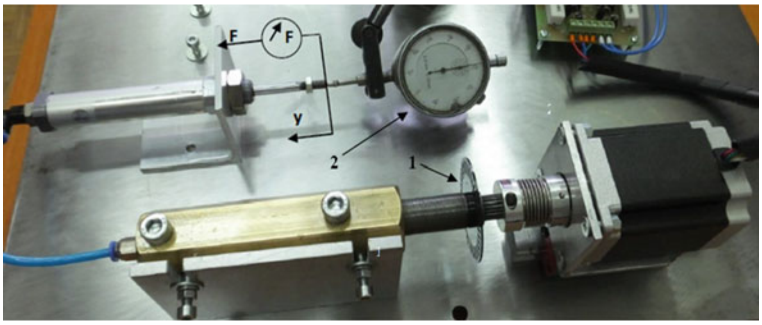

Fig. 11 Setup for precision test including a scale wheel (*1*) and a dial gauge (*2*)

6 Conclusions

Design of a hydraulically driven unit converting rotational motion into linear motion has been developed. Behaviour of the device has been modelled. A prototype has been constructed and experimentally evaluated. The first tests have given promising results regarding both precision and stiffness of the device. As far as the former is considered, the outcome also coincides with results of numerical simulation.

After implementation of further amendments, the device can be potentially used to drive hand prostheses, surgical manipulators or industrial manipulators. The design of the unit allows to place the driving actuator at a desired distance to the executing actuator, i.e. they can be separated in a way the driving actuator is placed outside the patient's body while the executing actuator—inside. The device can be also used in industrial manipulators, ensuring high stiffness and precision.

In future work, it is necessary to conduct tests evaluating the correctness of the positioning following a series of runs with different values of applied load. In addition, the variant of the prototype including driving actuator without any additional internal elements should be amended by means of tightening the thread at the interface between the piston and the cylinder. To reduce leakage to the minimum, the fissure between these threads should be less than 5 μm. Operation of the unit, in which the corrected actuator will be used, should be also tested.

Furthermore, to implement the unit in the medical equipment, material of which the actuators are manufactured should be changed to, e.g. surgical steel that can be used in direct contact with body fluids. Hydraulic oil should be replaced with some fluid that will not do harm to the patient in case of leakage—saline can be used for this purpose. However, it should be mentioned that, due to different bulk modulus, the stiffness of the unit will be changed, and thus tests of the device should be repeated. Last but not least, the unit must have its size changed (minimised) in order to use it for medical purposes—this conclusion applies in particular in the case of applying the unit to manipulate fingers of hand prostheses.

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