Development and Testing of the Mechatronic Gripper with Two Fingers

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***Abstract*—The article describes the problem of developing a novel gripper with two fingers using a differential gear. In the proposed solution, the fingers maintain parallel orientation to each other throughout the entire working area, consisting compact design of the gripper itself. The mechanism has two degrees of freedom, one for closing fingers and second for rotating the gripper. The novel approach is the way of drive transmission by using a differential gear connected to two DC motors located behind the gripper mechanism, which contributes to the reduction of its dimensions near the working area. There are force sensors on the fingers of the gripper allowing to grasp the object with a given force. A controller has been integrated in the gripper, which implements the developed control algorithm, including the coupling of the motors in the differential drive and feedback from the force measurement carried out by force sensors. Geometry has been selected for the proposed gripper scheme. The mechanism simulation tests were carried out in a program for dynamic analysis of multibody systems. The prototype of the gripper was assembled. Structure parts were made in FDM technology**

Keywords—differential, four-bar linkage, FDM, prototype, multibody simulation,

I. Introduction

Manipulators are an integral part of modern industry. The possibility of automation of repetitive movements makes it possible to produce parts at mass scale with low costs. One of the essential tasks for manipulators is to transport produced parts and to position them in space, for example in the CNC milling machine. To do this, manipulators are equipped with grippers - special effectors designed to grasp the part, move it to its destination - providing high stability during the movement - and release it there. There are plenty of criteria to categorise the grippers. One of the most basic ways is to divide them into mechanical and non-mechanical grippers [1][2]. The mechanical ones are the most commonly used in industry thanks to the possibility of designing devices for all kind of manipulation tasks. Among them we can distinguish soft grippers, which work E.g. imitating human fingers [3], using pneumatics [5] or SMART materials like fluid elastomer actuators (FEAs) or electroactive polymers (EAPs) [4]. Apart from that, there is a wide range of classic (non-soft) grippers, which are made of rigid parts. Interesting examples might be robots that use visual systems and force sensors designed to collect the strawberries [6], a parallel gripper with shape-memory actuators [7], and a 3-finger universal gripper that can use both outer and inner surfaces to hold the object [9]. Although soft grippers allow us to hold non-regular and non-rigid or flat parts, and they are being intensively studied - both numerical models [3] and physical constructions of these kind of grippers [5] - in most of the cases it is not economically reasonable to use them. Mechanical grippers, both rigid and soft, are characterized by a large variety of kinematic solutions due to their wide range of applications [2]. For example, in the industry there are often grabs with parallel, radial or bellows fingers [10]. Maintaining the parallelism of fingers across the whole spectrum of movement is a very desirable feature, but it usually involves the need to ensure the linear movement of fingers. The problems are both the size of the fingers themselves and the drives necessary to control them. The dimensions of drive systems are a very common problem in industry. Large gearboxes require a lot of space, while hydraulics requires a supply of working medium. Among the former, the systems with planetary gears, which allow to obtain large gears while maintaining small dimensions, are increasingly popular [11]. They are used in various fields: from classic drive systems, where space is limited, through devices e.g. for pipe inspection [12] and other mobile robots [13], to purely industrial robots [11]. One of the varieties of planetary gearboxes is the differential gear - with 2 degrees of freedom, known for example from differentials in cars. This article presents a solution of a mechatronic gripper with parallel fingers, using a differential mechanism in the propulsion system. The designed kinematic chain of the four-bar linkage, used in the construction of fingers, allows catching larger objects while maintaining small dimensions. The use of a differential gear allows to minimize significantly the size of the drive, while providing 2 degrees of freedom of grabbing. In this case, these are: clamping of fingers and rotation of the gripper. In addition, pressure sensors are mounted on the fingers, which significantly broadens the range of application of the gripper, e.g. for catching elastic objects. In the next part of the article we will discuss in detail: mechanical solution, electronics and gripper control algorithm. The models created during the design process will be presented, as well as the physical prototype of the device.

II. Concept

From a mechanical point of view, the gripper's design is based on 2 main modules: a differential drive system and a kinematic chain based on a four-bar linkage to achieve the desired movement of the fingers - maintaining mutual parallelism over the entire range of movement. Both of these modules will now be described. The differential gear concept is based on 2 drives with gearshaft ends. One of the wheels is connected to the outer wheel of the gearbox and the other to the inner wheel located on the gearbox core. The outer and inner wheels are connected to each other via satellites on the

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carrier. The rotation of the outer wheel is responsible for the rotation of the entire effector around the axis, and together with the carrier, the screw is rotated, which further drives the four-bar linkage and is responsible for closing and opening the clamp fingers. This allows movements such as turning the gripper without dropping the object being held. The kinematic diagram of the gearbox is shown in Fig. 1.

The formulas describing the movement in the gearbox were derived from Willis' formula. The relation between the speed of rotation of the clamp and the rotation of the carrier that drives the movement of the fingers through the lead screw and the speed of the motors has been established. Where M1, M2 are motors speed, N1 is speed of the lead screw, N2 is speed of the gripper rotation equal to that of the gear wheel K4, ri are rays of the corresponding Ki gears. The markings as shown in Fig. 1. The formulas are shown below.

$$N_1 = \frac{-M_1 r_1 + M_2 r_2}{r_3 + r_4} \tag{1}$$

$$N_2 = M_1 \frac{r_1}{r_4} \tag{2}$$

The base of the movable part of the clamp is attached to the outer wheel K4, which rotates with the outer wheel. There are 2 linear guides mounted at the ends. There are fixed joints of four-bar linked. A lead screw was run between the guides in turn. The trolley and nut on the screw and the linear guides convert the rotary motion into linear motion. By means of an additional beam ended with pins and an extension of one of the elements of the four-bar linkage, the drive is transferred from the trolley to the parallelogram and, consequently, to the effector. At this stage of the work, the effector is one of the four-bar linkage beams, which allows to demonstrate the nature of the work of the tip, and in particular to maintain the mutual parallelism of the fingers throughout the range of work. The design of the gripper allows the use of fingers of different shapes, so you can adjust the gripper to the objects which it will work with. Eventually, this element can be expanded for a specific manipulation task. The range of finger movements is unchanged. However, the maximum value of the opening of the fingers can be increased if there is no need to close them completely. When fingers are closing, the total length of the gripper is extended.

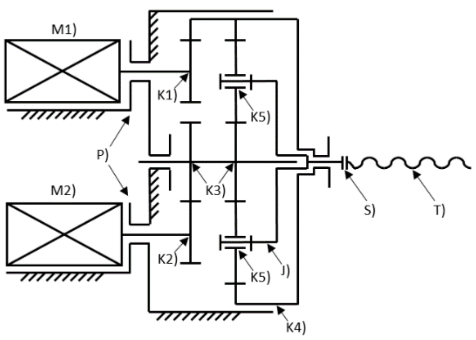

Fig 1. Kinematic diagram of the planetary gear module. Motor output wheels K1) and K2), Inner core and centre wheel K3), Outer centre wheel K4), Satellites (2) K5). Designations of other drawing elements: Carrier J), Motors M1) and M2), Gripper base P), Flexible coupling S), Lead Screw T).

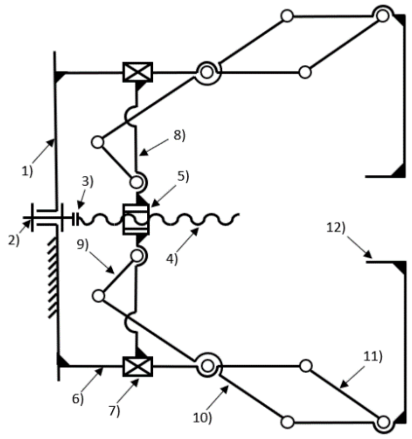

Fig 2. Kinematic diagram of the clamp's executive part. Planetary gear outer wheel (base) 1) , Carrier: 2), Clutch: 3) , Lead screw 4), Nut 5), Linear guide 6), Linear bearing 7), Trolley (nut and line bearing connector) 8), Additional spherical plain bar 9), Components of the spherical plain side 10) and 11), Effector, actuating element 12**).**

Fig. 2 shows the kinematic diagram of the execution element. The final design of the differential has external dimensions: 108mm diameter and 42mm height. It uses teeth with module 2. It consists of central wheels: external 47T and internal 15T, as well as a pair of 16T satellites placed on a rotating carrier. The gearbox is connected to a pair of gripper drives attached to the base via 12T gears on the motor shafts. The gripper is driven by two DC motors equipped with encoders with an effective resolution of 170.6 pulses per revolution. A FlexiForce A201 pressure sensor, shown in Fig. 3 is fitted to the fingers.

The ATMega328P microcontroller is responsible for controlling the system. Communication with the user takes place by means of UART transmission - the user controls the gripper with a PC, he is also constantly informed about motors speeds and pressure sensor indications. In the first mode of control the gripper is controlled by the operator who defines the set speeds for the motors. The motors are controlled by means of a feedback loop using the PD regulator. The speed information read from the encoders is taken into account when checking the motors. The operator can read out the force sensor indications in real time. In this mode of the control, the information read from the pressure sensors is not included in the control loop. In the second control mode, the feedback loop is also based on the PID regulator. The signal is controlled by data read from the force sensors. The operator is able to set the setpoints.. In this mode, encoders data is not used in the control process. The operator can read out force sensor readings in real time.

Fig 3. FlexiForce A201 attached to finger

III. Simulation

Simulation research of the designed mechanism was made in a multibody dynamic analysis program ADAMS. For that purpose, a special model was made. All major dimensions are compatible with other models of the gripper. The model was checked for any potential collisions. Maximum range, up to the singular point of the effector, was specified. The fingers have total range of motion of 80mm.

For the next step, maximum speed for the process of fingers closure was specified at the level of 10mm/s. Fig. 4 shows angular velocity of the second motor M2 during a constant-velocity movement of the fingers in the entire range of motion. Maximum value obtained during the simulation is 1350RPM and it responds to the moment of maximum fingers' opening.

Based on the dynamic simulations, required parameters of the motors were specified. For this purpose, two tests were carried out. In the first one a constant force momentum with a value of 5,5Nm was applied to the fingers in the axis of rotation of the gripper. The value of 5,5Nm is derived from a force of 100N that needs to be applied to a door handle to turn it and from the width of the door handle. Maximum force momentum of the first motor M1, that is responsible for the rotation of the entire gripper was 1,5Nm, For the second motor M2 it's only 0,0002Nm, so it's insignificant. The second simulation assumed a maximum squeezing force of 200N of the fingers in their work range. Fig. 5 shows force momentum in the drives. In the 3rd second of the simulation, the fingers were at their maximum opening, in the 9th second they are closed. Maximum values of the momentum were 0,033Nm for the first motor M1, and 0,104Nm for the M2 drive.

Based on the simulations that were carried out, it was possible to choose appropriate motors for the assumed manipulation tasks.

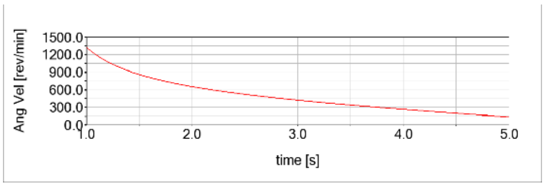

Fig 4. Angular velocity of the second motor M2 during the closure of the fingers at the constant velocity of 100mm/s in the entire range of motion.

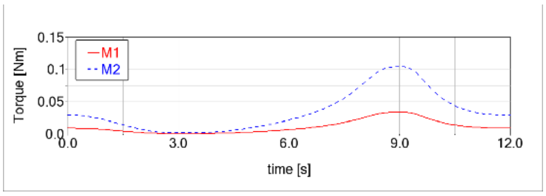

Fig 5. Force momentum of the drives in the entire range of motion of the fingers with a constant squeezing force of 200N.

IV. CAD model and physical prototype

The construction of the gripper was designed using Autodesk Inventor. Fig. 6 shows its visualisation. Main dimensions are in Figs. 7 and 8. Due to the design of the fingers and the four-bar linkage, the finger opening range is 0 - 60 mm. Fig. 9 shows a physical prototype of the gripper, on which a series of experiments was carried out. These tests are described in Chapter V.

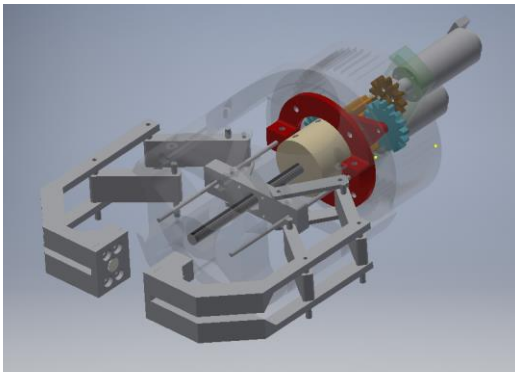

Fig 6. Visualisation of the CAD model of the gripper.

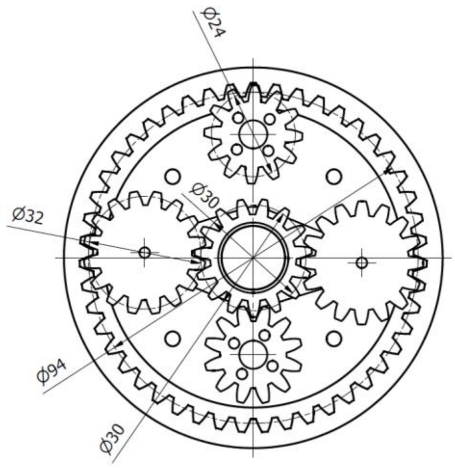

Fig 7. Main dimensions of the differential gear of the designed gripper.

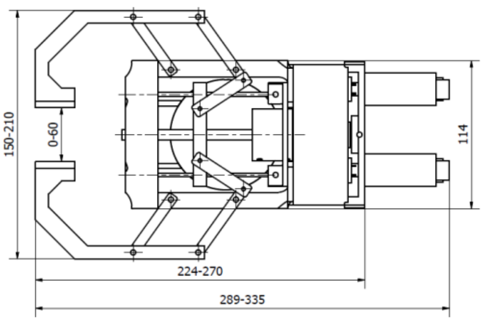

Fig 8. Main dimensions of the entire gripper (with its fingers closed and at maximum opening).

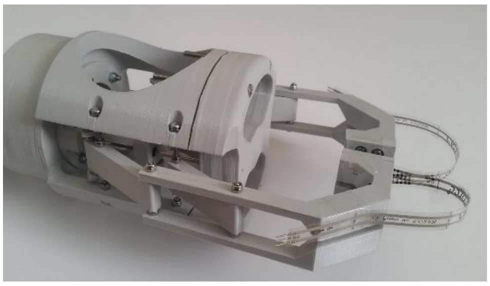

Fig 9. A view on the physical prototype of the gripper.

The prototype was built up using FDM technology. For the process the parameters were: nozzle size: 0,4mm, layer thickness: 0,2mm. The prototype was made of PET-G material. This material is characterized by a higher mechanical strength than PLA, and a relatively low technological process associated with its extrusion.

V. Experiments

Functionality of the physical prototype of the gripper was tested in the first test. The task was to grasp and hold various types of objects, without any additional cover on the fingers. The objects to hold were: a rigid cube, a rigid cylinder and a flexible ball. The results are shown in Figs. 10, 11 and 12.

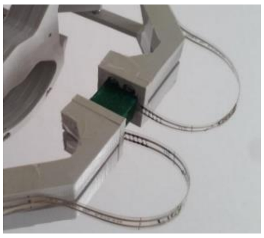

Fig 10. Stiff cube.

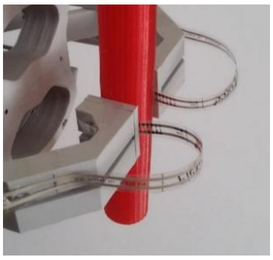

Fig 11. Stiff roller.

Fig 12. Elastic ball.

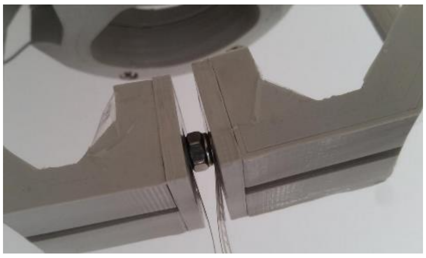

Fig 13. The gripper holding the test object during the second experiment.

In all of the cases, the object was held stably. None of the test objects was deformed or damaged in any way. Due to the imperfect shape of the fingers pads, these tests were based on speed control. Some objects did not adhere correctly to the force sensors, which distorted the measurement signal.

In the next step, the effect of the rotation of the effector on the force with which the object is held was tested. The experiment consisted of grasping a small object - with a size matching the force sensors surface - and then applying the rotation of the effector. Sampling time during the test was 80ms. Fig. 13 shows the object held during the experiment.

The results of the second experiments are shown in Figs. 14 and 15. The first chart shows the set and the measured velocities of the drives M1 and M2. The second chart presents the measured grasping force of the fingers.

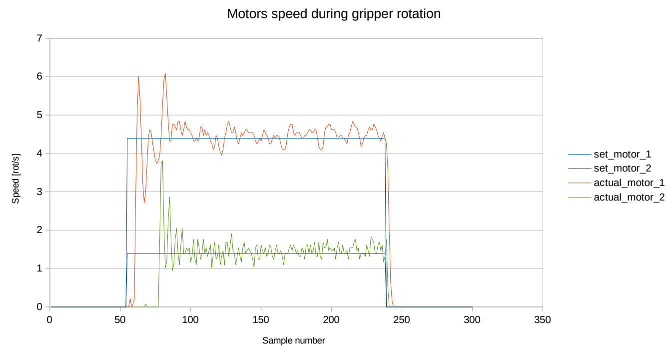

Fig 14. Angular velocities of the motors.

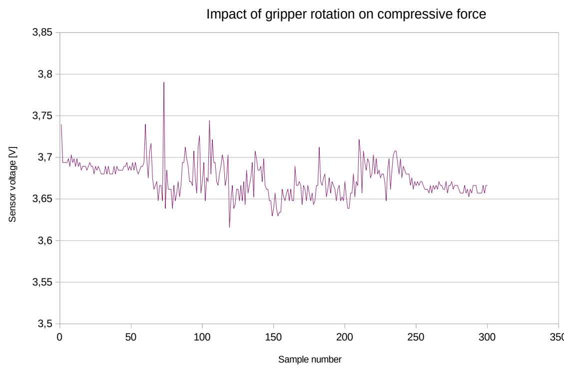

Fig 15. Raw force sensor voltage signal.

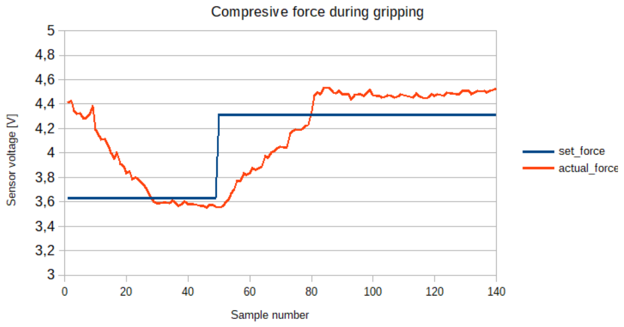

Fig 16. Raw force sensor voltage signal.

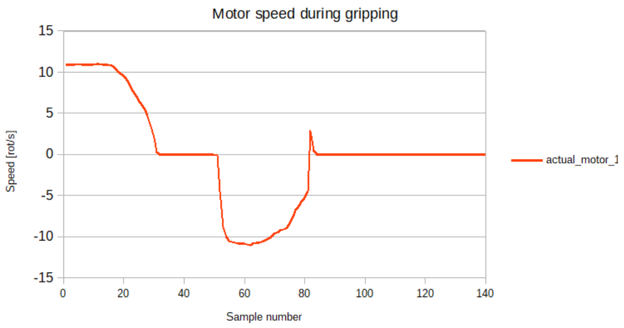

Fig 17. Angular velocities of the motors.

The results show that the control of the motors can still be optimised and that both motors may have a significant impact of the grasping force of the gripper.

The third test consisted of grasping a flexible ball with a given force. The force values, related to the sensor voltage, were selected experimentally. Fig. 16 shows the force sensor indications and the set force, while Fig. 17 shows the speed of the motor responsible for closing the gripper fingers.

VI. Discussion of the Results

The synchronization of the drives proved to be problematic - the motors used as well as the control method proved to be insufficient. The change in the force exerted by the gripper fingers on the grasped object is shown in Fig. 16. At the moment of starting the effector revolutions (samples 50 to 250) the signal oscillates significantly. The measuring method with sensors can also be enhanced to be more accurate, because during the static holding of the object the signal oscillates as well. In order to improve the performance of the mechanism, better quality motors should be used, as well as more precise PID regulator settings. It will also make sense to use other force sensors. Perhaps the performance of the gripper will improve the use of a wider spectrum of control of the voltage applied to the motor, and thus control its speed and the use of higher resolution encoders. The approach to sensor mounting should be changed. With the current setting it is possible to grab only rigid objects not exceeding the size of the sensor pad, or vulnerable elements. he fingers should be interlinked with the sensors. It seems reasonable to place sensors inside the finger structure.

Rigid objects with larger dimensions do not have sufficient contact with the sensors. The stiffness of the gripper is not sufficient. Tension elements that are too thin and slack in the gear mechanism cause great steering inaccuracies. In order to solve this problem, it will be necessary to carry out further research in this direction, or to completely change the approach to the production of the grapple. Changing the length of the gripper during operation can be problematic when used with classic commercial manipulators. However, the gripper was designed as part of a modern manipulator, where a dynamic changing the TCP position during operation is possible.

VII. Summary

The concept of two fingers gripper with differential gear was prepared. The multibody dynamic model was created and simulations were performed to obtain basic parameters for further development. The 3D model was created and a prototype of the gripper was built. Parts of the prototype were created using FDM technology. The physical model is fully functional - the gripper has two degrees of freedom and is able to capture objects. The use of differential gear allows multiple revolutions of the effector. Some elements require refinement. The correction of rigidity of the structure is significant. The looseness and flexibility of the mechanisms parts made it impossible to obtain a greater force on the gripper fingers. Further work involves the use of drives equipped with encoders with higher resolution as well as the improvement of drive speed control algorithm. The four-bar linkage mechanism on which the finger is attached can be improved by dimensional optimization. Modification of the differential gear, which can significantly affect the parameters of the device, is also considered.

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