

# MODIFICATIONS TO THE EFFECTOR FOR MEASUREMENT OF GRIPPING FORCE

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The article describes modifications to the effector of a manipulator arm proposed in order to increase the accuracy of jaw force measurements. Gripping force measurement is performed using strain gauges. Their proper positioning and connection minimize not only the influence of the position of the centre of gravity of the manipulation object on the jaws but also the effect of temperature changes around the measuring area. The possibility of altering the magnitude of gripping force was incorporated into the robot control application. This greatly increases the security of handling and increases the number of items that can be possibly gripped. Modified effector parts were subjected to stress analysis, with emphasis on the elimination of stress peaks that would not occur in real parts. The article also describes the design of the mechanical modification of the effector, which would allow the continuous rotation of the jaws of the effector.

## KEYWORDS

measurement of gripping force, effector, strain gauge, manipulator arm, stress analysis

## 1 INTRODUCTION

Technical systems with effectors are deployed still more and more not only in industry but also in areas such as military, healthcare, aerospace and others. Effectors can manipulate even with fragile, elastic or dangerous objects where it is essential to secure the maximum security of the operation. Failure could result not only in damage to the handled object and its surroundings but also in health injuries or even death of human workers.

For save grip and subsequent transport, the correct gripping force must be obtained. This can be estimated based on information about the handling object (strength, weight, the centre of gravity, possible gripping surfaces, etc.). However, these parameters are not always known. In this case, the gripping force can be determined for example by sensors and various methods [Lim 2014, Chuah 2014], by operator experience, or by the trial-and-error method.

It is not possible to set the grip force on the effector correctly without measuring it. The more precisely the force amplitude should be set, the more precisely it has to be measured. This article focuses on measurement of the grip force of an existing effector and the problems associated with modifications of the effector. Due to the design of the effector, it was not possible to provide the gripping force with the required precision. For this reason, the effector was modified by adding a set of sensors from which it is possible to obtain more accurate information about the actual gripping force. The installation of

these sensors also required a change in the existing gripping mechanism construction.

## 2 ORIGINAL STATE OF THE EFFECTOR

The original manipulator arm with effector was designed to handle various objects, especially in the outdoor environment. The jaws were able to generate a maximum gripping force of 600 N. This force is sufficient for transport of objects of manipulation weighing approximately 20 kg if the centre of gravity of the object is in the middle of the jaws. The kinematic structure is a parallelogram – this ensures a permanent parallelism of the jaws, independently on their opening. The original effector is shown on Fig. 1

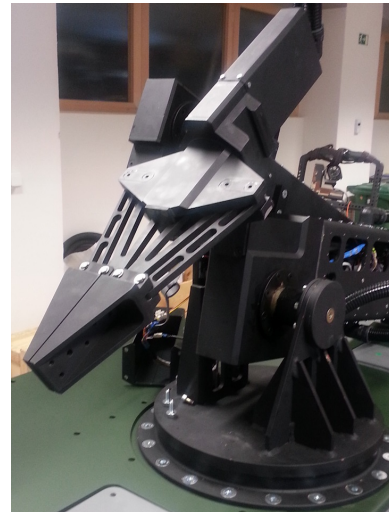


Figure 1. Original state of the effector

Practical testing showed that some objects of manipulation were deformed or destroyed by the gripper; or dropped due to insufficient gripping power. This has brought the motivation for modification resulting in better measurement and adjustment of the gripping force.

The original effector was able to measure the force between the jaws only by measuring the current in the direct current (DC) motor driving the jaws. However, this measurement was very inaccurate because of errors caused by a large variable friction in the mechanical parts of the effector, especially in drive gears.

## 3 METHODS OF GRIPPING FORCE MEASUREMENT

Several methods can be used to measure the gripping force on the effector. For example, industrial sensors can be applied to the gripper interface [Robotiq 2017] or on any part of the effector that transmits the jaw force [HBM 2016]. A popular way is to connect FSR (force-sensing resistor) sensors directly to the jaws. This measurement is simple, inexpensive, but not very accurate [Labounek 2014]. Various piezoelectric sensors can also be used, wrapped in an elastic substance transferring the force on the sensors. These sensors are, however, typically designated for measurement of dynamic forces [Chuah 2014]. An extremely high measurement accuracy (up to 11 mN) was achieved with the FGB (Fibre Bragg Grating) sensors on a surgical effector. However, the measurement range was very narrow (0 to 10 N) [Lim 2014].

Strain gauges rank among the most accurate and most suitable sensors for accurate measurement of forces in a wide range of forces and ambient temperatures. The most used are

resistance and semiconductor strain gauges (the latter are characterized by higher sensitivity) [Kminek 2005, Novak 2007].

To measure the gripping force on the effector, semiconductor strain gauges were used, mainly because of their high accuracy, sensitivity, a wide range of operating temperatures and small dimensions.

#### 4 APPLICATION OF STRAIN GAUGES

It was necessary to find a suitable place for the application of strain gauges, but it was not desirable to apply them directly on the jaws of the effector, as they can be modularly replaced by other jaws or working tools during the operation. Therefore, the strain gauges must be applied to some other part of the structure that transmits the gripping force. There are several such places on the effector. The first considered option was the drag links - see Fig. 2. Strength analysis of the links revealed that their deformation is dependent not only on the magnitude of the gripping force but also on the actual point of application of the force acting on the jaws. Because of this problem, the solution was eventually abandoned. The Fig. 2 shows different tensions on the drag links with the same gripping force, where on the left image the force acts near the edge of the jaws and on the right image at the centre of the jaws.

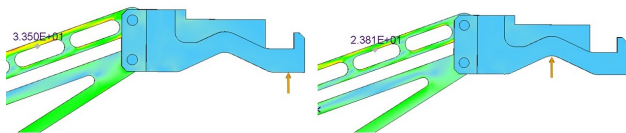


Figure 2. Tension in the drag link for different point of application of the same gripping force

The most suitable place for the application of strain gauges proved to be (after simulation tests) the nut of the trapezoidal screw – see Fig. 3. The nut is driven by an electric motor, which creates the gripping force. The thread is isosceles trapezoidal, ensuring self-locking. Once the desired grip force has been reached, the power on the motor can be turned off, and the grip force will not decrease. This not only saves electricity but also increases the safety of the system against a power outage.

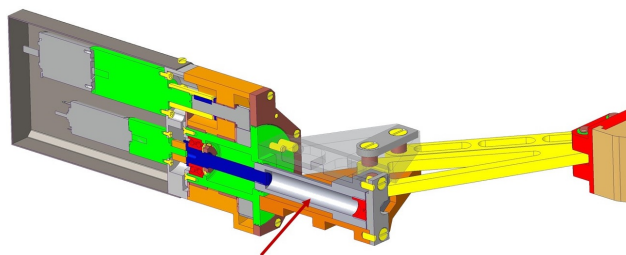


Figure 3. Inner parts of the effector (the arrow shows the position of the nut)

In the Creo Parametric Mechanism extension, it has been found that the axial deformation of the nut (the gripper rod) is not dependent on the gripping force point of action; in contrast to the previously mentioned situation with drag links. Creo Parametric was also used to ascertain the course of the axial force in the nut with a constant gripping force, depending on the jaw opening – see Fig. 4. This relation is necessary for conversion from the measured axial force to the gripping force.

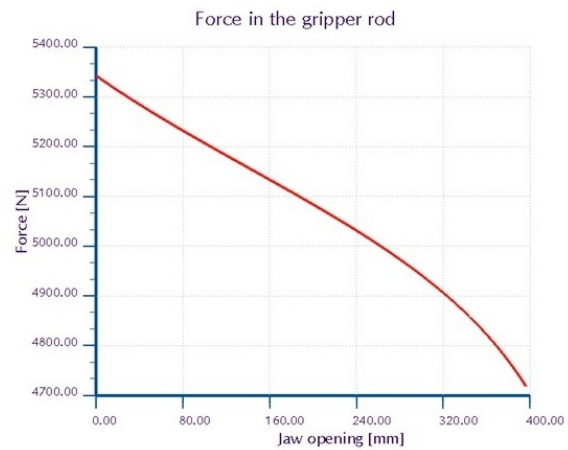


Figure 4. Course of the axial force in the nut in relation to the jaw opening (constant gripping force)

The relation can also be found mathematically by analysing the ratio of the jaws mechanism kinematics structure – see Fig. 5.

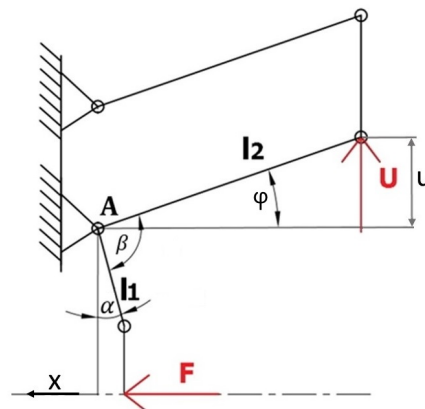


Figure 5. Kinematics scheme with points of force action

Value  $u$  represents the opening of the jaws, parameter  $x$  is the axial displacement of the nut and the constant angle  $\beta$  is given by the mechanism construction.

The overall ratio of the mechanism is composed of several partial ratios and can be described as:

$$p_u = \frac{d_u}{d_x} = \frac{d_u}{d_\varphi} \cdot \frac{d_\varphi}{d_x} = \frac{l_2 \cdot \cos(\varphi)}{l_1 \cdot \cos(\varphi + 90 - \beta)} \quad (1)$$

where  $d_u$ ,  $d_x$  and  $d_\varphi$  are differentials of the  $u$ ,  $x$  and  $\varphi$  values respectively; and  $l_1$  and  $l_2$  are link lengths.

The relation between the forces  $U$  and  $F$  can be deduced by the principle of virtual work applied on the whole mechanism. It is important to mention that the force  $F$  is split between two forces  $U$  – one for each jaw, thus:

$$-F \cdot \delta x + 2 \cdot \delta y = 0 \rightarrow \frac{U}{F} = \frac{1}{2} \cdot \frac{\delta x}{\delta u} = \frac{1}{2} \cdot \frac{1}{p_u} \quad (2)$$

The final relation (ratio) between forces  $U$  and  $F$  is obtained by substitution of equation (1) into equation (2):

$$\frac{U}{F} = \frac{1}{2} \cdot \frac{l_1 \cdot \cos(\varphi + 90 - \beta)}{l_2 \cdot \cos(\varphi)} \quad (3)$$

The ratio is not constant; it depends on  $\varphi$ . The function (3) is important for conversion of axial force into gripping force and is implemented in the control system software.

## 5 MODIFICATIONS OF THE EFFECTOR MECHANICAL CONSTRUCTION

One part of the effector had to be modified for application of the strain gauge – the bolt nut. The modification consisted of a groove milling to create a place for the strain gauges. The nut before modifications is shown in the Fig. 6 at the top. The bottom of the Fig. 6 contains two views of the nut after treatment with arrows pointing towards the areas for strain gauge application. In the groove, the strain gauges are protected against mechanical damage.

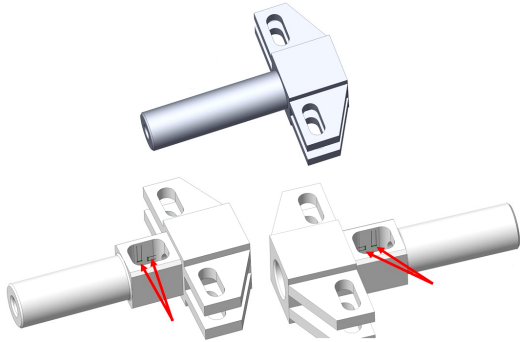


Figure 6. Mechanical modification of the nut (arrows show locations of the strain gauges)

Four wires must be connected to the strain gauges. For measuring and testing purposes, they were led along the effector into the measuring unit. This, however, prevents the continuous rotation of the effector (allowed by the construction of the manipulator arm wrist). To maintain the continuous effector rotation, a proposal was made to modify the remainder of the effector.

### 5.1 Continuous Effector Rotation

To ensure a continuous rotation of the effector, a detailed 3D model was designed. The inner part of the structure has been adapted for wiring the strain gauge. To avoid twisting of the cable, two slip rings were used to guide the wiring from the rotating part to the fixed part. The signals from the strain gauges are analogue and the slip rings would cause a large error due to the rotation. Therefore, the analogue signal from the strain gauges must be digitized before going through the slip rings. A digital converter specifically designed for strain gauge measurements was used for this purpose. This converter sends the measured signal through the RS 485 communication interface over the slip rings to the effector controller. The digital signal is no longer disturbed when passing through the slip rings. Fig. 7 shows a cross-section of the modified effector with slip rings.



Figure 7. Cross-section of the modified effector (arrows show locations of the slip rings)

### 5.2 Stress Analysis

The modified parts of the effector had to be checked by a stress analysis. The stress analysis was performed in the Creo Simulate program. Results of analyses depend on the correct

way of defining the computational model. In the case of analyses of separate components, there is a problem in defining "constraints" that are typically defined on model surfaces. Constraints defined in this way do not have the possibility of loosening rotation, which in most cases does not correspond to reality. The result of the analysis then shows false spikes at the constraint location.

Fig. 8 (left) shows the clutch with colour-coded attachment location; on the right image is visible the stress peak in this area.

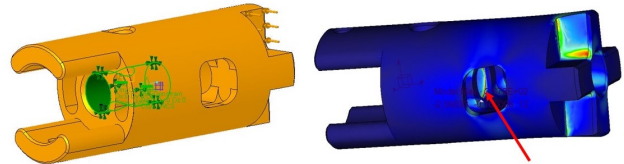


Figure 8. Stress analysis of a clutch

Therefore, it is advisable to use the ability to perform stress analyses of assemblies using contact analyzes. The component being analyzed is connected by means of contact surfaces to a fictitious component that is attached by "constraints". Contacts are created between the components so that the component to be analyzed has the necessary degrees of freedom. Contacts can be defined without friction or with a specific shear friction value. For the first analysis, it is appropriate to define the contacts without friction. The entire computational model is subjected to a contact analysis. When evaluating the results, it is necessary first to assess the behaviour of the whole assembly – the way of deformation. Accordingly, the calculation model can be adjusted so that the deformation mode matches the assumed behaviour of the model. The stress distribution is evaluated only on the components that need to be analyzed.

The Fig. 9. shows the clutch assembly and the trapezoidal screw. At the top, the fictitious modelled part is shown. In the middle and bottom, the stress is shown after a FEM analysis. The bottom image is a cross-section of the component for evaluation of stress at the real point where the clutch is mounted. The results of the analyses show that the stress peaks have shifted to the fictitious component that is not subject to the assessment of the results.

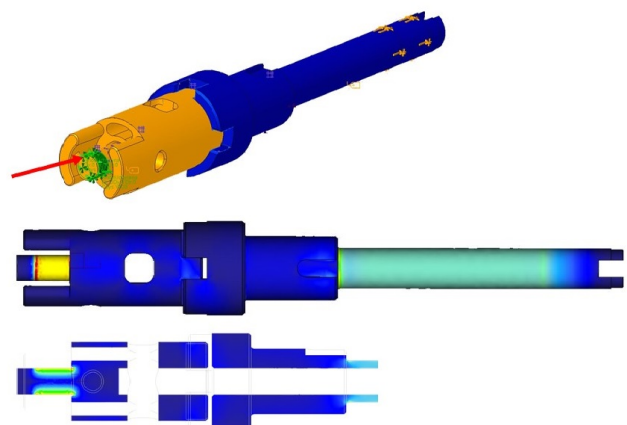


Figure 9. Stress analysis of an assembly

## 6 TEMPERATURE COMPENSATION

The strain gauges are connected to a full bridge, thus ensuring compensation of the temperature dependence that is considerable for semiconductor strain gauges. However, due to the temperature coefficient tolerances of the individual strain gauges, a small measurement error occurs due to temperature

effects. This was additionally compensated by experimental measurement of the signal connected to the bridge at two different temperatures. First, the entire system was cooled down to 10 ° C and the output signal was measured, then the whole system was heated to 50 ° C and again the signal was measured once more. This determined the amount of the bridge difference. In the same way, all individual strain gauges were measured to determine which of them responded the least to temperature changes. A short copper wire was then attached to this bridge. This wire compensates for the change of the signal. After completing this additional compensation, the temperature impact on the accuracy of the measurement was only negligible.

## 7 CALIBRATION OF THE SYSTEM

The strain gauges are connected to a bridge. Their voltage is amplified by an amplifier and measured by the analogue input of the measuring unit. The measured voltage must be converted to force in the corresponding units (Newton). This was done by experimental measurement using a digital force meter located between the jaws. Twenty measurements were made at different gripping forces; increasing the gripping power gradually, and then decreasing. Afterwards, a mathematical function (curve) describing approximately the relationship was found. The mathematical description of the curve is integrated into the control unit, which translates the measured tension to the corresponding gripping force. The Fig. 10 shows the testing of strain gauges on the effector.

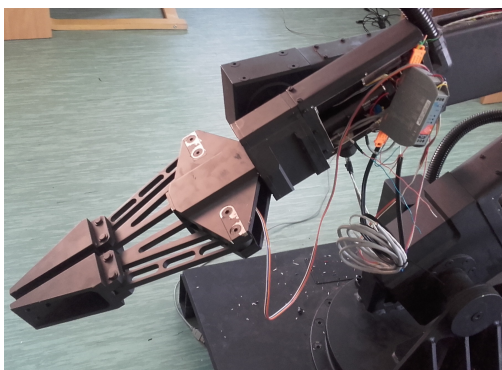


Figure 10. Effector testing

## 8 CONTROL SYSTEM

The control system of the robot allows real-time monitoring and controlling of the gripping force. The mobile robot operator can see the actual amplitude of the gripping force on his screen and can freely adjust it, as needed. The effector itself is further equipped with a camera and the images from this camera are also displayed on the screen. This combination – monitoring of the object of manipulation through the camera together with precise feedback and control of the gripping force – allows the operator to handle objects with much better safety and sensitivity.

Fig. 11 shows a sample screenshot of the control application; the effector icon is displayed in the bottom left corner (no gripping force is detected at the moment and the jaws are fully closed). A detail of this icon in a different situation is also shown in Fig. 11.

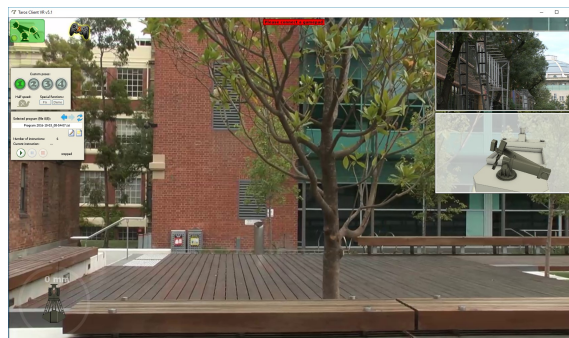


Figure 11. Screen of the mobile robot control system

## 9 CONCLUSIONS

The effector was modified for accurate measurement of the gripping force. Strain gauge sensors were applied to a selected part of the gripper. A 3D concept was designed to allow continuous effector rotation. In the current state, the control application shows the operator a camera image of the effector surroundings together with the amplitude of the gripping force. The force can be controlled in real time. However, the operator himself must determine how big gripping force is needed to safely hold the object. In some cases, the operator may not know the weight of the object. Then he must rely on the trial-and-error method and carefully increase the gripping force if the object appears to be slipping from the jaws. With some practice, the operator is able to handle a wide range of objects, even a fragile object such as a raw egg (see Fig. 12), or quite heavy objects to with the maximum gripping force of 600 N.



Figure 12. Final practical testing of the effector (holding a raw egg with the gripping force equal to 30 N)

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