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Intelligent Interpretation of Multiaxial Gripper Force Sensors

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Mechanical grippers are key components of handling devices in automated assembly systems. For complex handling tasks these grippers can be equipped with additional force measuring modules. This paper presents the prototype of a gripper with fingers made of sensorial material. These gripper fingers contain six single force sensors and can measure forces along multiple axes. The results of the experimental investigations of the sensor performance are shown. It is also demonstrated how further information about the handling conditions can be derived by the computational combination of the sensor signals. A sensor network will enrich the capabilities of the gripper fingers.

Handling, Measurement, Sensorial material

1. Introduction

Automated assembly systems are often equipped with mechanical grippers with two or more parallel fingers. They are one key component for the performance of handling devices. Force sensors, which are attached to the gripper system, enhance the functionality of the handling device by enabling the gripper system to grasp pressure sensitive objects and helping to pick up objects with unknown shape and orientation. Furthermore, the gripper gains the ability to perform force adaptive joining operations or force adaptive path corrections. Since the fingertips of grippers with force measurement systems do not need a work piece specific geometry, they can be adapted to new production setups more easily. Therefore, they help to overcome problems that arise from frequent product changes in flexible assembly systems. Conventional force measurement systems for mechanical grippers are heavy and expensive. They are produced in the form of modules that can be added to the basic gripper. It can be distinguished between modules that are installed at the wrist of a robot system and modules that are joined to the finger of a gripper. Wrist sensors are usually multi-component sensors but they increase the size of the end-effector and add mass, so that the payload is decreased [1]. Although wrist sensors are multi-component, they cannot measure the gripping force. Therefore finger sensors are suitable. They are lighter but harder to install. If both, gripping forces and external forces, should be measured two systems have to be installed, which results in a heavy and complex end-effector. The evaluation units of the sensor modules are usually placed in the central control unit of the handling device and require therefore a lot of wiring which makes it difficult to quickly exchange the end-effector.

Grippers with fingers made of "sensorial material" have the potential to overcome these drawbacks. They add only little mass to the gripper, allow force measurement along multiple axes and enable decentralized control strategies. Sensorial material is a new class of material that is able to retrieve information about the surrounding and its own condition and to communicate it [2]. It is based on miniaturized sensor elements and chips and their embedment in a host material. The sensorial material allows the integration of the sensing elements directly into the gripper finger. Several sensors can be placed on one finger and allow multiaxial force measuring. The different sensor nodes will be connected to a sensor network and will perform fast and robust computing of the sensor signals [3]. In a first development step a conceptual design based on strain gauge equipped gripper fingers has been introduced [4]. These strain gauge equipped gripper fingers are a preliminary stage to a passive sensorial material. This paper presents the gripper finger design and the performance quality of the sensor system by experimental investigations. It is also demonstrated how further information about the gripper condition can be derived from the sensor data by intelligent interpretation. Finally it is explained how the transition from a passive to an active sensorial material will be reached in the future.

2. Integration of force sensors in gripper fingers

To evaluate the concept of a gripper with sensory gripper fingers, a prototype has been implemented at the Bremen Institute for Mechanical Engineering. This prototype consists of a commercial actuator which is equipped with two identical novel gripper fingers. Each gripper finger is cut out from a single aluminum block and contains three force sensors that are integrated

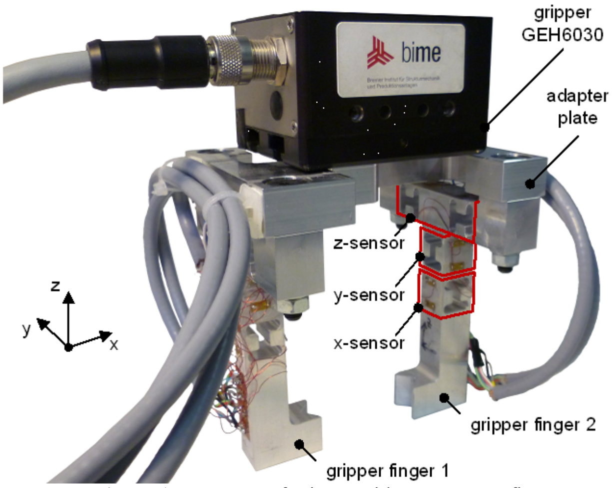

Figure 1. Prototype of gripper with two sensory fingers.

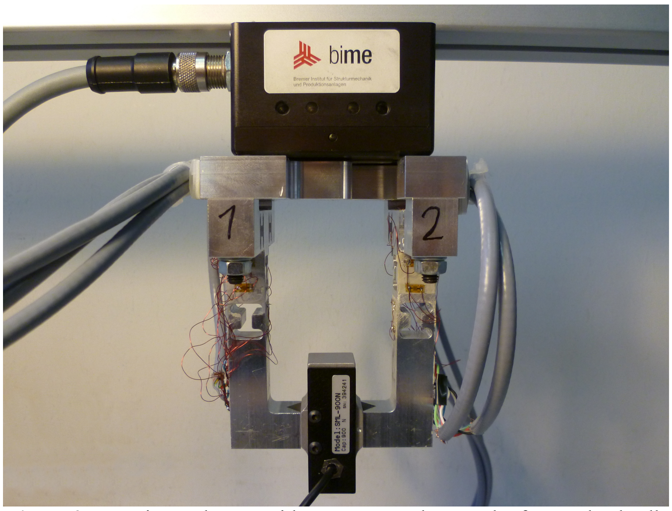
Figure 2. Experimental setup with prototype and grasped reference load cell.

in the basic finger structure. The force sensors are based on strain gauges that are connected to Wheatstone bridges. The three force sensors in every finger are arranged orthogonal to each other so that every sensor should ideally measure forces only along one basic axis (x, y, z). To support the physical separation of the basic force components into x-, y- and z-forces, special designed H-shaped cut outs have been milled into the gripper finger structure. These help to reduce the interferences between the different directions. This means, for instance, that the sensor for forces along the x-axis should not respond if the applied force only acts along the y- or z-axis.

Figure 1 shows the prototype of the gripper. The three sensors at the second finger are highlighted by red frames. It can be seen that the z-sensor is formed by two H-shaped cut outs. Each of these cut outs is equipped with four strain gauges, which results in eight strain gauges for the whole z-sensor. They are connected to a single Wheatstone bridge and can therefore compensate resistance changes that are caused by deformations from torque inside the z-sensor. Such a torque results from forces along the y-axis which cause bending around the x-axis inside the z-sensor. The design of the finger has been evaluated by finite element analysis as well as by practical experiments. A single finger was clamped to a fixture and static loads were applied to the fingertip in different directions. The sensors showed adequate measuring accuracy and a very good separation of the basic force components [4]. For evaluation of the sensor performance under varying load conditions and for investigation of the sensor behavior during real gripping situations, further experiments have been carried out. The results are presented in the following sections.

3. Evaluation of sensor performance

3.1. Description of experimental setup

The gripper prototype described in chapter 2 was mounted to a test stand like depicted in figure 2. A modular data acquisition system (DAQ) was used to measure and record all signals in real time. The DAQ also contains analogue output terminals that are used to drive an external amplifier which delivers the required voltage and current to power the DC motor inside the actuator of the gripper. An additional load cell is also connected to the DAQ and delivers the reference signal which is then compared with signals from the gripper fingers. The load cell has a rated capacity of 900 N, has a nonlinearity of 0.05 % and a hysteresis of 0.05 %. This measuring accuracy is higher than the expected measuring accuracy of the gripper fingers. Therefore the load cell can be used as reference signal during the investigation of the sensor performance. Different experiments were carried out with the single gripper fingers as well as with the whole gripper assembly. The fingers were tested on their behavior under dynamic load increase and on the influence of the contact point on the measuring accuracy. To evaluate the behavior of the force sensors under dynamic conditions the load cell was pushed against the fingers from different directions. For each pushing all signals of the gripper finger and the load cell were recorded simultaneously. This procedure was repeated for different contact points at the fingertip to survey the influence of the position of the contact point on the measuring accuracy.

3.2. Results and interpretation of experiments

Figure 3 shows exemplarily the performance of the x-sensor of finger 2 for a load that is applied to the tip of the finger along the x-axis. X_2 is the signal of the force sensor and F_r is the reference signal of the load cell. Since X_2 and F_r are so close to each other that they cannot be distinguished in the graph, the relative error $\Delta X_2/F_r$ is also depicted. It can be seen that the mean relative error is below 1 %. Except for small forces the relative error stays nearly constant over the whole measuring range. For investigation of the influence of the contact point the absolute measuring error was recorded for loads at different contact points. Figure 4 shows result for three different points at the bottom of the finger. For better illustration only the best fit straight lines are depicted.

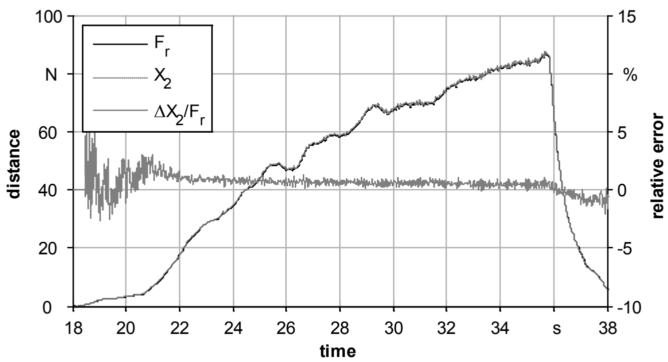

Figure 3. Performance of x-sensor under dynamic conditions.

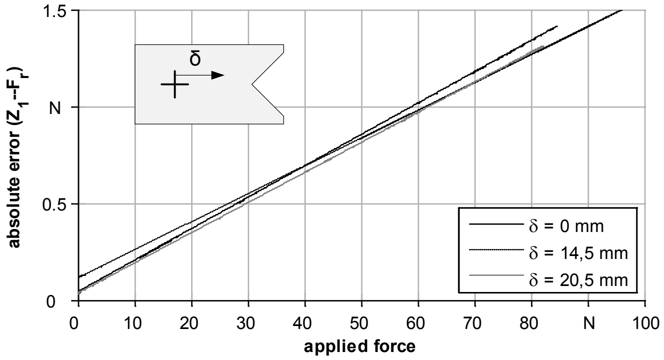

Figure 4. Performance of z-sensor for varying point of contact.

It can be seen that the measuring error varies with the contact point. Although this happens within a small range, it is recommended to apply loads during calibration at the most likely contact point, which is at the very tip of the finger. For contacts that occur away from the tip, the measuring error might then be greater. But this is acceptable, since this type of contact normally only occurs during collisions and for collision detection the measuring error is of minor importance.

4. Advanced interpretation of sensor signals

Until now, the sensor signals have been treated separately and no computation has been performed on the signals. But to use the data from the sensory gripper during the control of handling processes further information has to be derived by combining the single data streams. The most important information is the actual gripping force that acts on the grasped object. The gripping force is also called internal force since it only appears inside the gripper system and cannot be observed from the outside. If no external force acts on the gripper fingers, the absolute values of both x-sensors in fingers 1 and 2 should be equal to the gripping force. But if an additional force acts from the outside there might be a load shift from one finger to the other. Therefore the actual gripping force is derived by calculating the arithmetic mean of the measured forces X_1 and X_2.

$$F_g = \frac{X_2 - X_1}{2} \quad (1)$$

To evaluate the equation, experiments with the gripper and the reference load cell were carried out. Therefore the load cell was placed upright on a stand between the fingers of the opened gripper. Then the gripper was closed while the signals were recorded from the DAQ. This experiment was repeated for different preset motor voltages. The graph in figure 5 compares exemplarily for one single run the calculated gripping force F_g with the

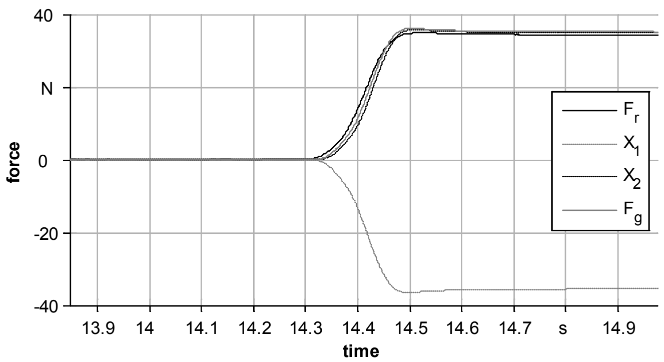

Figure 5. Calculation of gripping force from x-sensor signals.

measured forces X_1, X_2 and the measured force of the reference load cell F_r. It can be seen that F_g is equal to F_r which proves that the assumptions have been correct and that equation (1) is suitable to calculate the gripping force.

Besides the internal gripping force, the value, direction and contact point of external forces are of interest during the control of handling processes. These external forces can be caused by unforeseen collisions with other objects or during the joining with another object. Figure 6 depicts a free-body diagram of two gripping fingers and a grasped object. From the equilibrium of forces along the x-axis the following equations for the external force $F_{ext,x}$ can be derived.

$$F_{ext,x} = X_1 + X_2 \quad (2)$$

Similar equations can also be derived for external forces along the y- and z-axis.

$$F_{ext,y} = Y_1 + Y_2 \quad (3)$$

$$F_{ext,z} = Z_1 + Z_2 \quad (4)$$

To get the direction and value of the overall external force the equations (2) to (4) can be combined to a vector equation.

$$\vec{F}_{ext} = \begin{bmatrix} F_{ext,x} \\ F_{ext,y} \\ F_{ext,z} \end{bmatrix} = \begin{bmatrix} X_1 + X_2 \\ Y_1 + Y_2 \\ Z_1 + Z_2 \end{bmatrix} \quad (5)$$

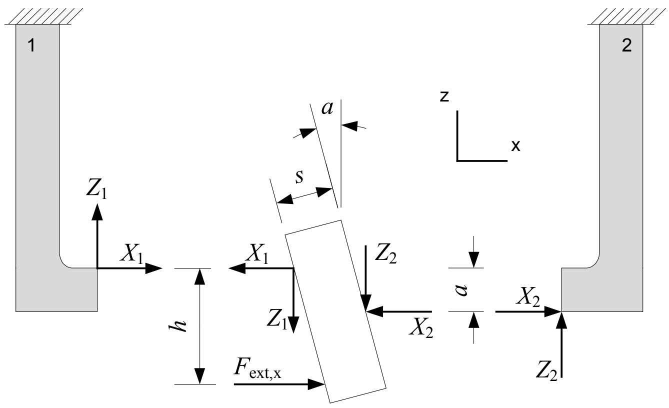

Figure 6. Planar free-body diagram of gripper finger and grasped object.

Experiments were carried out to evaluate the equations. A rectangular workpiece was grasped by the gripper and then the load cell was used to push against the workpiece from different directions. A ball-shaped tip that was screwed to the load cell reduced the contact area to nearly point contact and allowed the measurement of the contact point position. The graphs in figure 7 demonstrate the experiment results for an external force along the x-axis (a) and the z-axis (b). The experiments with y-sensors delivered comparable results.

The graph in figure 7 a) shows an interesting behavior of X_1 and X_2 for external forces over 15 N. If a positive external load is applied along the x-axis, the absolute value of X_2 increases while the absolute value of X_1 decreases by the same amount at the beginning. This is the expected behavior and results in a constant overall gripping force F_g. But when the external force $F_{ext,x}$ further increases, X_1 starts to increase together with X_2 which represents an increase of the gripping force, although the gripper actuator is not powered. Figure 8 depicts the reason of this phenomenon. Due to the leverage effect of the workpiece, the gripper fingers are spread apart. Since the fingers cannot draw aside due to the self-locking transmission of the gripper actuator, the spreading results in elastic deformation of the finger and therefore increases the gripping force.

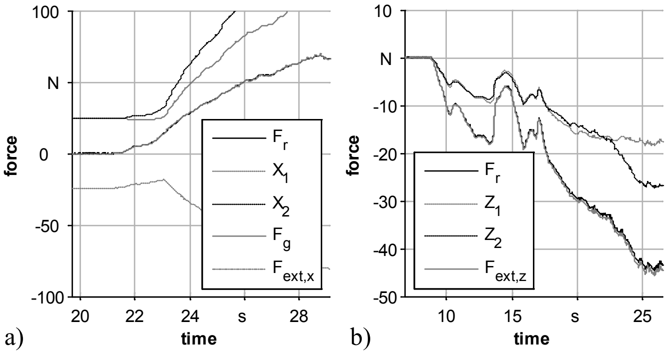

Figure 7. Calculation of external force from a) x-sensors and b) z-sensors.

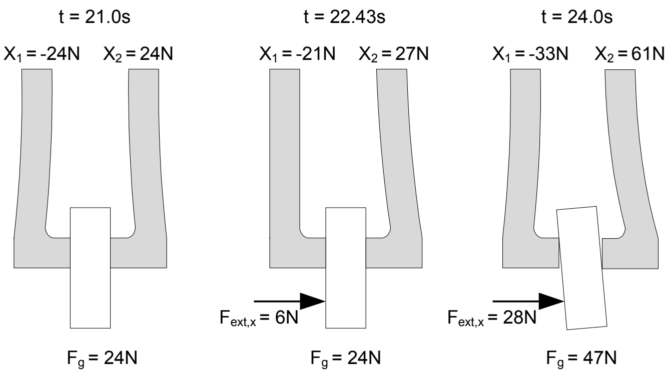

Figure 8. External force increases gripping force due to leverage effect.

The leverage effect allows the determination of the contact point from the force sensor signals. The equilibrium of moments around the y-axis delivers equation (6). The distance w between the both finger tips is a function of the tilt angle α, but for the expected forces α is very small and it is assumed that $w(\alpha(F_{ext,x})) = w(0°)$, which equals the width s of the workpiece.

$$h = \frac{X_2 a + Z_2 s}{X_1 + X_2} = \frac{-X_1 a - Z_1 s}{X_1 + X_2} + a \qquad (6)$$

In this case the contact point is described by the distance h form the upper side of the finger tip, like depicted in the free-body diagram in figure 6. Figure 9 shows the result of an online calculation of h for the same experiment as in figure 7 a). Equation (6) is only when the leverage effect is in progress.

5. Sensor network for gripper sensors

For principle experimental investigations the evaluation of sensor signals was performed on an external central processing unit. The DAQ provided the necessary measuring and control hardware. This is not in the sense of a sensorial material, since a sensorial material should perform decentralized preprocessing of the sensor signals and should communicate ready-to-use information to high level control systems. The next generation of sensory gripper fingers should head towards an active sensorial material. The transition from a passive to an active sensorial material component will be performed using decentralized active sensor nodes that are arranged in a sensor network integrated in the finger structure. Each sensor node will provide signal acquisition, data processing, and communication. The integrated sensor network will lead to increasing functionality and robustness. Using a central processing system requires manual calibration of all six

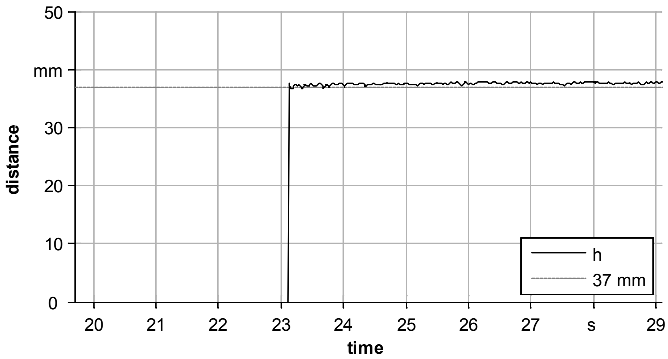

Figure 9. Calculation of external force contact point from sensor signals.

sensors. Self calibration and adaption to the change of environmental conditions through the network of sensor nodes will ease initiation and the usage of the measurement system.

6. Conclusion

This paper demonstrates the concept of a mechanical gripper with sensory gripper fingers made of passive sensorial material. The gripper fingers contain six single sensors and can perform multiaxial force sensing of internal and external forces. Experiments showed that the measuring accuracy is of suitable quality for handling process control, if the calibration is done at the tip of the gripper finger. Collisions can be detected at all points below the x-sensor section. Therefore the measuring accuracy is of minor importance. The six single sensors deliver data about the acting forces divided into basic force components along the x-, y- and z-axis. To get information about the effective gripping force or external load, further computation has to be performed. The gripping force can be calculated by the arithmetic mean of the both x-sensor signals. The direction and value of an external load can be derived from the combination of all six signals. Due to the leverage effect it is also possible to determine the contact point of an external load at the workpiece. The transition from a passive to an active sensorial material by the integration of decentralized sensor nodes connected via a network is part of the future research.

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