A Modular Underactuated Gripper with Force Control System

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Abstract: A design of an underactuated electromechanical gripper with force control algorithm is presented in this paper. The key feature of the gripper is the ability to grasp fragile objects and objects of a complex shape. Such advantages are due to the usage of elastic joints and force sensitive resistors embedded in modules of gripper's fingers. Also low cost and mass of the presented device makes its application rational for a larger number of robotic systems. Proposed force control system is based on PI control and passification approaches that provide tuning simplicity and good performance in the case of unknown environments. Experimental results show the efficiency of proposed solution.

1 INTRODUCTION

Development of cheap and mobile mechatronic complexes equipped with a grasping devices is an actively increasing area of robotics. Creation of universal grippers for mobile robots operating in unknown environment is an particular task (Bicchi, 2000; Choi et al., 2017; Ma et al., 2013).

Grasping devices for mobile robots should satisfy following conditions:

- low mass and dimensions;
- ability to grasp objects with unknown complex shape;
- ability of force interaction control;
- low cost and modular structure;
- low energy consumption, etc.

Low mass and energy consumption allow to install gripper on mobile robots with limited charge of battery. Low cost and modularity of the structure are preffered due to practical and financial reasons. In particular, the modular design significantly improves the maintainability of the device and its post-warranty service. On the other hand, a simpler construction usually ensures a higher reliability of technical systems (Telegenov et al., 2015).

Interaction with unknown environment may include accurate grasping for fragile objects and fast reaction in the case of active environment for damage prevention. There are three ways to solve this problem: use of tacticle sensors (as, for example, in Tegin and Wikander, 2005), adaptive (Bazylev et al., 2015) and robust (Margun et al., 2014) control laws, use of underactuated and compliant devices.

One can categorize grasping devices with three classes: mechanical, vacuum and magnetic. Magnetic grippers operate only with ferromagnetic objects. Therefore, further we do not consider this class. Vacuum grippers provide grasping of only objects with special form and structure. So we can not use them in unknown environment.

There are following classes of mechanical grippers: hydraulic, pneumatic and electric. Hydraulic grippers can apply the largest strength among all classes but provide low velocity, require massive pumps and a lot of energy (Lane et al., 1999). Pneumatic grippers are popular due to their light weight and compact size. The need of use compressors and impossibility of force and position precise control (usually only "bang-bang" control is available) are main disadvantages of this type. Grippers with electric motors do not require compressed air or liquid and provide position and force control. Comparison of different gripper types is in Table 1.

There are a lot of mechanical schemes for electric grippers which allow to grasp objects with complex shape. Some solutions are based on the use of elastic joints (see Camillo, 2014; Chen and Lin, 2004; Ma and Dollar, 2014; Ma et al., 2013; Zhang et al., 2018, etc). Simplicity of manufacture, modularity and low cost are the main reasons for the increased interest in such devices. However, the lack of force sensitivity prevents the use of these grippers in tasks that require

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Table 1: Comparison of gripper types.

	Hydraulic	Pneumatics	Vacuum	Electric
Grasping force	High	Low	High	Middle
Complex shape	No	No	No	Possible
Force control	Possible	Possible	No	Yes
Mass and dimensions	High	Middle	Middle	Low
Price	High	Low	Middle	Middle

precise grasping. In such cases expensive devices with multiple degrees of freedom (see, for example, Andersen et al., 2017; Camillo, 2014) or complex underactuated mechanics (as in Camillo, 2014) are used. The use of force sensitive systems on devices, as in Ma et al. (2013) and Ma and Dollar (2014), as a rule, leads to a significant complexity of the structure and loss of modularity. Thus, there is the development problem of devices with elastic joints preserving its benefits (simplicity, modularity, cost price) that have a force sensitive system. Since such systems are underactuated, a particular task is the synthesis of force control algorithms for precise grasping.

The goal of our project is to develop cheap and easy for production gripper with low mass, force control and possibility to interact with active environment. The paper organized as follows. Section 2 is devoted to the mechanical construction. Element base is in Section 3. Control algorithm and experimental results are provided in Sections 4 and 5. Finally, concluding results are given in Section 6.

2 GRIPPER CONSTRUCTION

Low mass-dimensional parameters, cost, modularity and possibility of force control are main parameters for our goal.

YaleOpenHand gripper with four fingers (Ma and Dollar, 2014; Ma et al., 2013) is chosen as a prototype for our device. The model of a differentially controlled pair of gripper fingers is presented in Fig. 1. Contraction-relaxation of fingers carried out due to the winding (unwinding) tension thread on the pulley by actuator in the gripper body. Simultaneous movement of fingers is provided by block system of the tendons (Fig.2) and only one servomotor. Flexible joints and phalangeal contact surfaces are made of polyurethane.

Object grasping is provided with the use of block

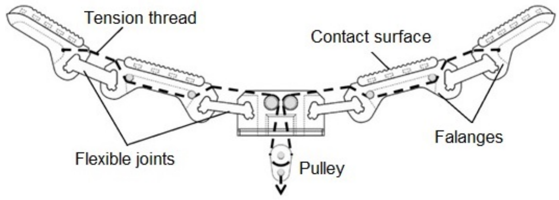

Figure 1: Differentially controlled pair of gripper fingers.

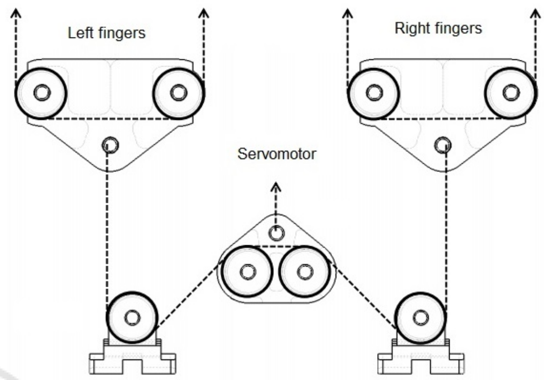

Figure 2: Block system.

system by movement of main roller fixed on the servodrive shaft. High-strength thread is used as the tendons. Grasping is carried out as follows:

- servodrive rotates the shaft;
- main roller on the shaft winds the thread;
- main block moves up;
- finger blocks moves down;
- move of blocks moves the fingers.

The construction was sufficiently reworked for force sensitivity implementation with save of functionality and modularity. First task caused by special arrangement of sensors that measure force of interaction. Sensors should be located directly under the contact surface in each phalanx of the fingers. Second task includes laying of wires, sensors connection with controller, preservation of device modularity.

Force sensitive system in each phalanx is performed in the form of removable modules to solve described problems. The information bus, through which data is exchanged with each module, is installed along the finger from the side opposite to the contact surface. Such solution eliminates the possible rubbing of wires during operation of the gripper. Sensor modular structure is in Fig. 3. A plate with a contact surface attached to it is inserted into the cavity above the force interaction sensor. This module is inserted into the cavity in each phalanx of the finger. Thus, in the case fingers are in contact with an obstacle (object of operation) all modules embedded in the

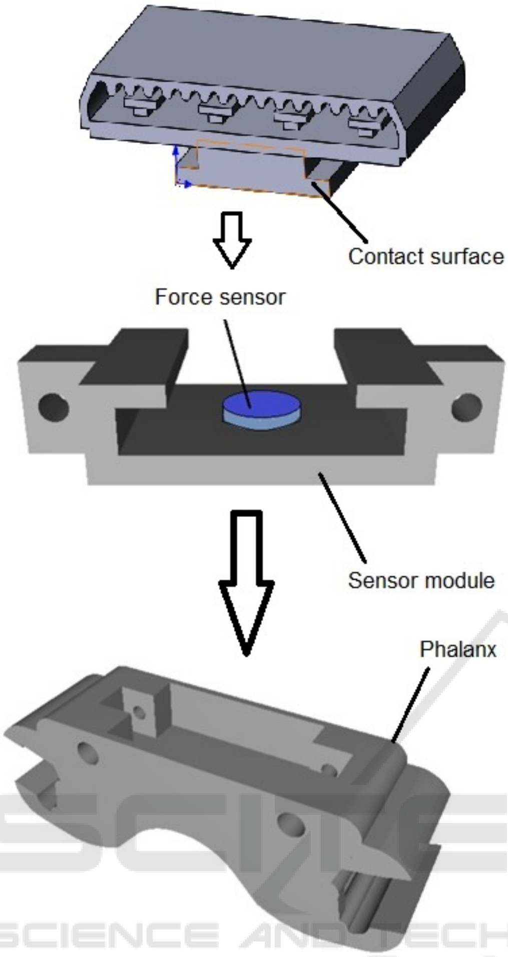

Figure 3: Sensor modular structure.

phalanges send force interaction data to the controller via information bus. It should be noted, developed structure allows simple change of sensor module and its connection to information bus (there is no need to disassemble all construction, replace full finger, etc.).

3 ELEMENT BASE

All mechanic details of gripper are made by 3D printing with FDM technology. The use of plastic sufficiently reduces mass of the gripper. 3D printing greatly simplifies manufacture process.

Elastic joint are made with casting of polyurethane. To prevent slippage and increase adhesion with the object of capture, the surface of the fingertips and phalanges are covered with a layer of more rigid polyurethane. Forms for casting were made by 3D printing. Polyurethane is widely used in industry due to the wide range of operating temperatures (from -60 $^\circ$ C to + 80 $^\circ$ C) and the ability to work in conditions of large alternating loads.

Servomotor Dynamixel MX-64 is chosen as gripper actuator. Its characteristics are in Table 2.

Table 2: Dynamixel MX-64 parameters.

Mass	g	126
Dimensions	mm	40.2 x 61.1 x 41
Gear	–	200:1
Interface	–	TTL half duplex
Encoder	–	360°/4096 (absolute)
Voltage	V	12
Torque	N · m	6
Current	A	4.1
Velocity	tpm	63

Force is measured via force sensitive resistors FSR-400 connected in resistive divider scheme. Its parameters are shown in Table 3.

Table 3: FSR-400 parameters.

Actuation force	N	0.2
Sensitivity	N	0.2-20
Resolution	–	Analog
Repeatability	%	± 2
Rise time	us	¡3
Tap durability	–	10 millions
Temperature range	°C	-40 – +85

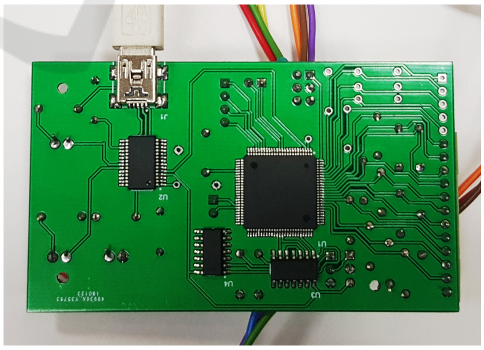

Figure 4: Electronic board.

Developed electronic board for the gripper is shown in Fig. 4. The board is based on microcontroller ATmega 2560 and provides connection with external devices by common interfaces (USB, I2C, SPI, UART), reading sensors data (up to 16 sensors), data processing, communication with servomotor, calculation of control algorithm.

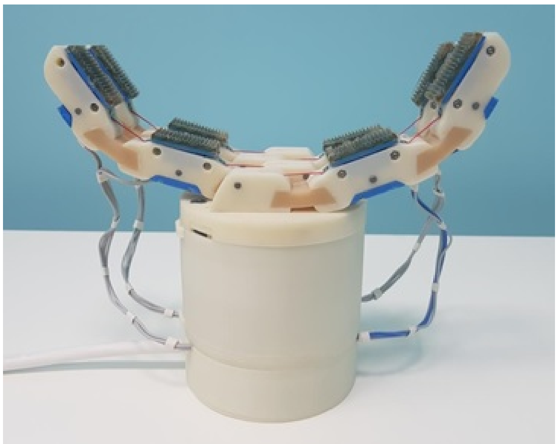

Figure 5: General view of the gripper.

Assembled gripper is illustrated in Fig. 5. Obtained gripper parameters are shown in Table 4.

Table 4: Gripper parameters.

Sizes	mm	223x100.5x192
Mass	kg	0.724
Voltage	V	12
Maximum power	Wt	36
Grasping time	s	1.122
Force range	N	0.5 – 7.5

4 CONTROL ALGORITHM

The goal of control algorithm is to provide desired contact force between surface of gripper fingers and grasping object. It is proposed to use the passification based method to ensure effective regulation (Groothuis et al., 2018). The control algorithm is designed in such a way that the energy of the plant is limited and, as follows, the plant is not unstable. In our case servomotor is an actuator of the gripper and fingers are the plant.

Consider energy transmitted to the plant for the period $(t_0;t_1)$:

$$\Delta E = \int_{t_0}^{t_1} \tau(t)\omega(t)dt = \int_{t_0}^{t_1} k_m i(t)\omega(t)dt, \quad (1)$$

where $\tau(t)$ is a momentum on the shaft of servomotor, $\omega(t)$ is an angular velocity of the shaft, k_m is a constant, $i(t)$ is a servomotor current.

Because of servomotor is a discrete system controlled by pulse-width modulation with small sampling time we have that $i(t)$ is a constant for $(t_0;t_1)$, where $(t_0;t_1)$ is a sampling time. Then

$$\Delta E = k_m i(t_0) \int_{t_0}^{t^1} \omega(t)dt = k_m i(t_0)(q(t_1) - q(t_0)), \quad (2)$$

where q is a rotation angle of the shaft.

Introduce a PI speed controller to control the force of interaction with the grasping object

$$\omega^* = \left(k_p + \frac{1}{s}k_i\right)(F^* - F), \quad (3)$$

where ω^* is a desired servomotor angular velocity, k_p and k_i are positive controller parameters, s is a differential operator, F^* is a desired force of interaction, F is a force of interaction.

PI controller includes an integrator. This may lead to unlimited energy transmitting in the case of unknown active environment and consequently to plant instability. To overcome this drawback we limit the amount of energy that the controller can transmit to the plant with finite state machine (Fig. 6).

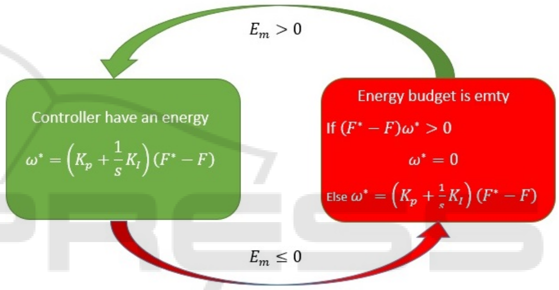

Figure 6: Finite state machine.

Let the controller has energy budget E_m. Then we have:

- in the case of energy transfer from controller to plant $(\omega^*(F^* - F) > 0)$ and energy budget is non-empty $E_m > 0$ then calculated control signal ω^* increases plant energy and the energy budget is reduced;
- if plant energy is reduced $(\omega^*(F^* - F) \leq 0)$ then we increase the energy budget by ΔE.
- if $(\omega^*(F^* - F) > 0)$ but energy budget is empty $E_m < 0$ then $\omega^* = 0$.

Schematically the proposed control algorithm is illustrated in Fig. 7.

Proposed algorithm includes advantages of PI controller (simple tuning and implementation) and advantages of passivity based approaches (passivity of closed-loop system, good performance in the case of unknown environments).

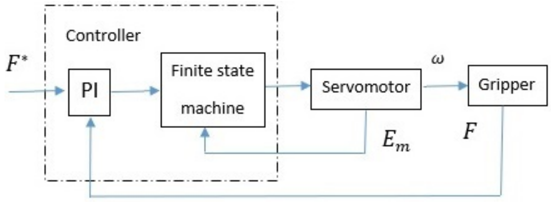

Figure 7: Control algorithm scheme.

Figure 8: Experiments.

5 EXPERIMENTAL RESULTS

Experimental research was conducted for the designed gripper. The task of experiments is to verify the grasping ability of the objects with different geometrical shape. For this purpose we used a cylindrical object (plastic can) and a complex shape object (walkie talkie) (Fig. 8). The control goal is gripping and withholding the object with a predetermined desired force.

Experiment parameters are chosen as follows: $F^* = 3N$, sampling time is $0.01s$, $k_p = 80$, $k_I = 1,1$, $k_m = 0.0075$, $E_m = 0.1J$. Experimental error transients are shown in Fig. 9–10 for the plastic can and walkie talkie, respectively.

Experimental results show that proposed control algorithm provides convergence of interaction force to the desired value.

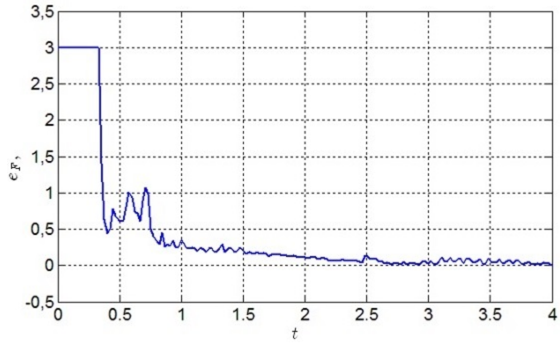

Figure 9: Transients of the force error for cylindrical object.

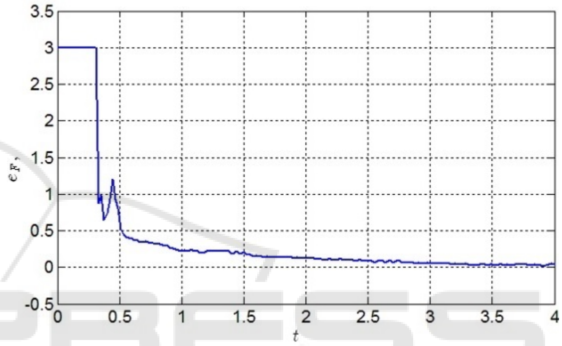

Figure 10: Transients of the force error for complex shape object.

6 CONCLUSIONS

Cheap and easy for manufacturing gripper is presented in the paper. Proposed construction allows to move four fingers of gripper with only one servomotor. Gripper allows to work in unknown environment and external disturbances due to use of elastic joints. Designed device is equipped with force sensitive system based on force sensitive resistors embedded in finger modules. Electronic board is based on ATmega 2560 microcontroller and provide the common interfaces for integration into various robotic applications. The proposed control algorithm is based on PI and passification approaches. Experimental results show good performance of presented solution.

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