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Novel Type Grippers for Small Objects Manipulation

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1. Introduction

The bulk of the contemporary requirements for grippers used in robotics, microrobotics and environment exploration, as well as industrial automation tasks are usually mutually incompatible and it is very hard to find an optimal technical solution that would satisfy the requirements of each specific field of implementation. There is a recent trend for even higher and stricter requirements for the capability of dosing of the applied force during gripper object manipulation of soft (surgery) or miniature objects (under a scanning electron microscope), remote robot teleoperation (hazardous environment exploration and sample extraction) and others. One of the possible alternatives of a device suitable for the increasingly demanding and diversified fields of application, as well as practical implementation of the functions required is the use of a new type of actuators with force, position and visual feedback [2, 3, 4, 5].

2. Gripper with linear actuation

2.1. Design and principle of operation

Fig. 1 shows the assembly drawing of the developed linear actuation gripper.

The linear actuators with a movable permanent magnet possess one important advantage, namely the simple design which makes them especially suitable in cases where the overall size has to be kept to a minimum.

Fig. 2 shows the construction of the developed gripper.

On the two ferromagnetic cores *1* and *2* are wound the windings *3* and *4*, which are powered in opposite directions. The permanent magnet *6* is situated in the air gap between both cores and has the possibility to move longitudinally parallel to the cores

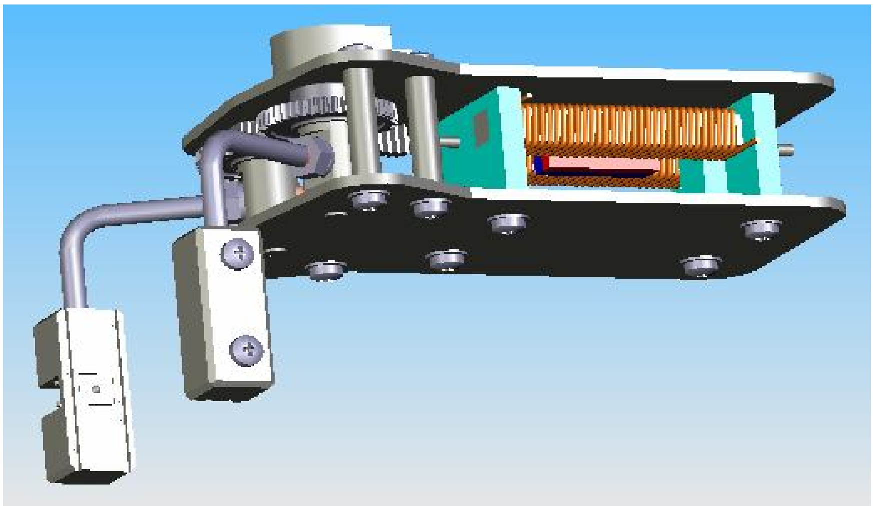

Fig.1. Assembly drawing of the gripper with linear actuation

together with the permanently fixed to it shaft *7* and gear rack *8*. The permanent magnet is magnetized in the direction shown and is made out of material NdFeB 40 MGOe. Both ferromagnetic cores are made of ARMCO.

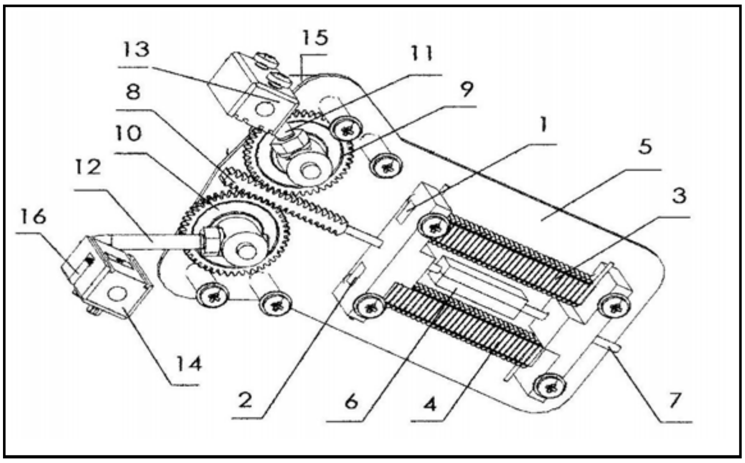

Fig. 2. The construction of the gripper with linear actuation:
1, *2* – ferromagnetic cores; *3*, *4* – windings; *5* – chassis; *6* – permanent magnet; *7* – shaft; *8* – rack; *9*, *10* – gears; *11*, *12* – fingers; *13*, *14* – gripper jaws, *15* – digital encoder; *16* – sensor FSS

The terminals of windings *3* and *4* are coupled in such a way to a DC power source that the electromagnetic forces produced as a result of the interaction with the permanent magnet poles S and N of the magnet *6* act in a single direction, i.e. the resultant force is parallel to the magnetic cores *1* and *2* and lies in the same plane. As a result of the force the magnet *6* is displaced in the direction of the force until the end position is reached or the voltage supplied is cut. Reversing the polarity of the supplied voltage results in an opposite direction of the force, which in turn causes displacement of the magnet *6* in the opposite direction.

2.2. Mathematical model of the magnetic field of linear electromagnetic actuators with a movable permanent magnet

According to the experiments done in [1] the mathematical model of the magnetic field of linear electromagnetic actuators with a movable permanent magnet in the general case is determined by the equation:

$$\nabla\times\left(\nu\nabla\times\vec{A}\right)-\vec{J}_e+\sigma\frac{\partial\vec{A}}{\partial t}-\sigma\vec{v}\times\vec{B}-\nabla\times\left(\nu\mu_0\vec{M}\right)=0, \tag{1}$$

where:

$\vec{A}$ is magnetic vector-potential, which in two- dimensional case is with only one non-zero component,

ν – reciprocal value of the magnetic permeability (1/m),

$\vec{J}_e$ – current density in the windings,

σ – specific electrical conductance,

t – time,

$\vec{v}$ – velocity of the moving parts,

$\vec{B}$ – magnetic flux density,

μ_0 – magnetic permeability of the air,

$\vec{M}$ – magnetization vector $M = B_r/\mu_0$, where B_r is residual magnetic flux density.

As for solving equation (1) it is necessary to know in advance a number of factors dependent on variables that change as a function of time, such as an algorithm for control of the power supplied to the windings, the characteristics of the elements responsible for determining the position of the movable part, as well as the friction forces involved during movement, which are dependent on the concrete mechanical construction, and so the experiments are made with static conditions and known current density in each winding, in which case equation (1) becomes:

$$\nabla\times\left(\nu\nabla\times\vec{A}\right)-\vec{J}_e-\nabla\times\left(\nu\mu_0\vec{M}\right)=0. \tag{2}$$

In occasion of flat parallel magnetic field, such is this case, the current density vector as well as the magnetic vector-potential have non-zero component only along an axis *z:*

$$\boldsymbol{A} = A\mathbf{z}_0,$$
$$\boldsymbol{J} = J\mathbf{z}_0.$$

Thus equation (2) becomes:

$$\frac{\partial}{\partial x}\left[\nu\frac{\partial A}{\partial x}\right]+\frac{\partial}{\partial y}\left[\nu\frac{\partial A}{\partial y}\right]=-J_e+\nu\mu_0\left[\frac{\partial M_y}{\partial x}-\frac{\partial M_x}{\partial y}\right]. \tag{3}$$

Equation (3) represents the mathematical model of the flat parallel magnetic field in the presence of permanent magnet [3]. Since the electromagnetic system of the actuator in the general case is open, the solving of the equation should be made in area with enough buffer zone around the linear actuator and with assigned homogeneous Dirichlet boundary conditions.

2.3. Operation of the device

During its longitudinal displacement along the axis of shaft *7* under the influence of the electromagnetic force the magnet *6* brings to motion the rack *8* and in turn rotates the gears *9* and *10* coupled to it. Depending on the direction of movement of the rack

8 rotates in either way, but in opposite directions the gears *9* and *10* with the attached to them fingers *11* and *12* and respectively the jaws *13* and *14*. Attached to jaw *14* is a FSS Low Profile Force Sensor (shown as element *16* on Fig. 2) produced by Honeywell [9] with dimensions of 4×4×10 mm.

The jaws of the gripper can be exchanged in a timely fashion depending on the concrete requirements of application at hand and the type of the manipulated objects. The FSS sensor can measure accurately the force applied during gripping in the effective range of 0 to 1500 g and due to his linear characteristic its output can be easily transformed into DC voltage. Another function of this sensor is to detect the moment of contact between the gripper jaws and the surface of the manipulated object, respectively the moment of its release.

A disadvantage of the implemented linear electromagnetic actuator is that it can be used only in combination with a device providing positional feedback. In this case this disadvantage is countered by the implementation of the encoder *15* shown on Fig. 2, which is coupled to the shaft of the gear *9*, again shown on Fig. 2. The finger *11* is fixed to the gear *9* and to the finger itself is coupled the exchangeable jaw *13*. As a result of the high measuring resolution of the encoder *15* the proper accuracy of positioning the gripper jaws is ensured [8].

The functioning of the device in different modes of operation is realized by controlling the value of the DC voltage supplied to the coils of the electromagnetic actuator and monitoring the output value of the encoder and the FSS sensor. Changing the polarity of the supplied voltage will correspondingly either open or close the gripper jaws. The speed with which this will happen is proportional to the value of the voltage supplied. When contact between the gripper jaws and the object to be manipulated is established (an indication of which is received by the FSS sensor output) the force thus applied upon the object is proportional to the supplied voltage as well. When working with automatically oriented symmetrical objects in the moment of contact the corresponding output value of the encoder gives accurate information for the dimension of the object between the points of contact with the gripper jaws. When used in closed-loop mode this information could be used for measuring the object dimension deviation from the desired target value. By rotating the gripper (around the *Z* axis) and thus taking several measurements of the object dimensions (by establishing contact with the gripper jaws each time) reading the encoder output the shape of the object could be identified or dimension deviation measurements along several planes could be performed.

After establishing contact with the manipulated object and subsequent increase of the force the gripper jaws exert on it (via increase of the DC voltage supplied to the actuator windings) the change of encoder reading (i.e. object deformation) could allow for determination of the hardness of the object, as well as the optimal gripping force which would allow for the proper execution of all desired manipulations of the object.

3. Gripper with rotary voice coil actuators (VCR)

3.1. Design and principle of operation

Fig. 3 shows the assembly drawing of the developed gripper [5] activated by rotary Voice Coil Actuator (VCR) RA29-11-002A made by BEI KIMCO, USA [7] – shown on Fig. 4.

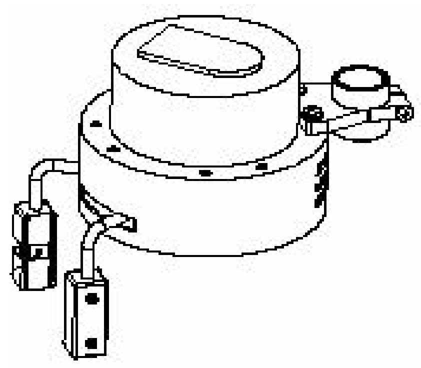

Fig. 3. Assembly drawing of the gripper with rotary actuation

The choice to use RA29-11-002A is made based on the following considerations:

- VCR possess a very high electrical-to-mechanical energy conversion rate and thus eliminate the eventual losses of using gearing, which usually leads to up to 70% overall efficiency;
- VCR provide cogging-free, hysteresis-free motion capable of extremely fine position sensitivity, limited only by the feedback sensor used to close the control loop;
- because the force is proportional to the current applied and VCR have linear force v.s. travel characteristics, the torque generated on the output shaft is the same along the whole displacement range;
- VCR distinguish themselves with exceptionally low electrical and mechanical time constants and the acceleration achievable with voice-coil actuators is unparalleled;
- this type of devices is characterized by exceptional reliability and flawless operation and do not need additional calibration or servicing.

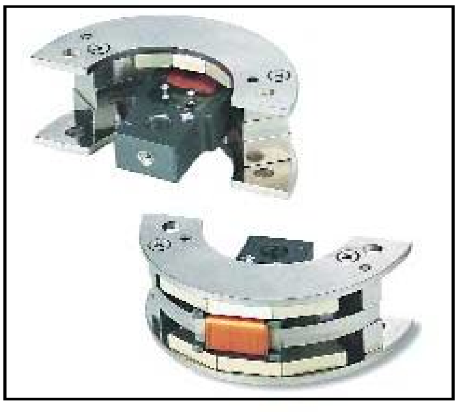

Fig. 4. Rotary voice coil actuator RA29-11-002A

In Table 1 are shown all of the more important technical parameters of RA29-11-002A Catalog of BEIKIMCO (from [7]).

Table 1

PEAK TORQUE *	OZ–IN	Tp	32
CONTINUOUS STALL TORQUE **	OZ–IN	Tcs	13.2
ACTUATOR CONSTANT	OZ–IN/√WATT	Ka	4.44
ELECTRICAL TIME CONSTANT	MICRO–SEC	Te	770
MECHANICAL TIME CONSTANT	MILLI–SEC	Tm	23
POWER I²R @ TORQUE 32 OZ–IN	WATTS	P	52.0
STROKE (ANGULAR)	± DEGREES		16
CLEARANCE ON EACH SIDE OF COIL	IN		0.025
THERMAL RESISTANCE OF COIL	°C/WATT	θth	9.7
MAX ALLOWABLE TEMP OF COIL	°C	TEMP	155
WEIGHT OF COIL ASSEMBLY	OZ	WTc	1.0
TOTAL WEIGHT	OZ	WTt	6.3

* 10 SEC @ 25°C AMBIENT, 155°C COIL TEMP
** 25°C AMBIENT, 155°C COIL TEMP

3.2. Construction

Fig. 5 shows the construction of the developed gripper [5].

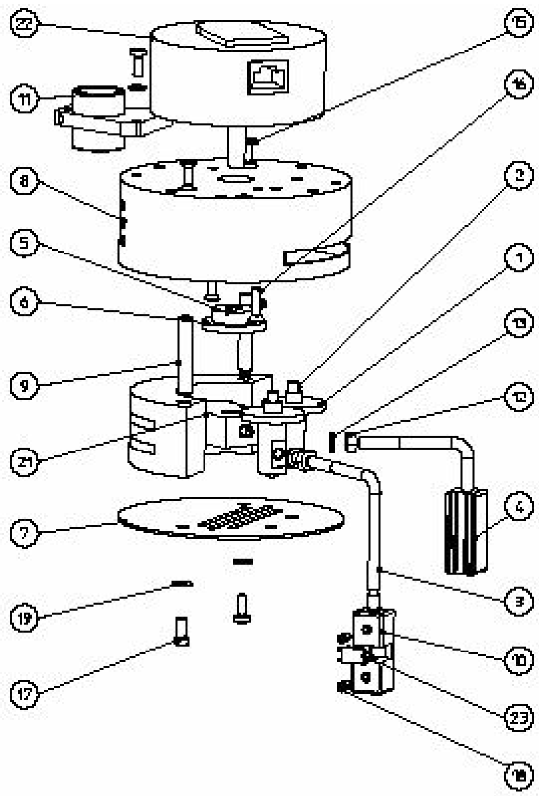

Fig. 5. The construction of the gripper with rotary actuation
1 and *6* – cogwheels; *2* – shaft; *3* – finger; *4* – jaw; *5* – hub; *7* – cover; *8* – corpus; *9* – pillar; *10* – measuring jaw; *11* – racket; *12* – hexagon nut; *13* and *19* – spring washers; *15*, *16*, *17* and *18* – screws; *21* – rotary actuator RA29-11-002A; *22* – encoder A2; *23* – FSS Low Profile Force Sensor

On shaft *2* of the VCR is mounted hub *5* together with the coupled to it cogwheel *6*. The cogwheel *6* is coupled to cogwheel *1*, which in turn is fixed to shaft *2*. When the VCR is actuated the cogwheel *6* rotates cogwheel *1* and shaft *2* in the necessary direction and then in turn the fixed to to the shaft finger together with the attached to it interchangeable jaw *4*. During this movement cogwheel *1* rotates in opposite direction the coupled to it third cogwheel with the analogically fixed to it shaft and correspondingly finger *3* together with the attached to it interchangeable measuring jaw *10*. On this jaw is mounted the FSS Low Profile Force Sensor (*23* on Fig. 5) manufactured by Honeywell [9] with dimension of only 4×4×10 mm (Fig. 6).

Fig. 6. FSS Low Profile Force Sensor

Table 2 shows all of the more significant parameters of this sensor Catalog of Honeywell (from [9]).

Table 2

PERFORMANCE CHARACTERISTICS @ 5.0 ± 0.01 Vdc Excitation*, 25 °C [77 °F]				
Parameter	**Min.**	**Typical**	**Max.**	**Units**
Null Offset	-15	0	+15	mV
Operating Force	0	–	1500	grams
Sensitivity.	0.1	0.12	14	mV/gram
Linearity (B.FS.L.)**	–	± 1.5	–	% span
Repeatability @ 300 g	–	± 10	–	grams
Null Shift				
25 °C to 2 °C [77 °F to 35.6 °F]	–	± 0.5	–	mV
25 °C to 40 °C [77 °F to 104 °F]	–	± 0.5	–	mV
Sensitivity Shift				
25 °C to 50 °C [77 °F to 122 °F]	–	5.5	–	% span
25 °C to 0 °C [77 °F to 32 °F]	–	5.5	–	% span
Input Resistance	4.0 K	5.0 K	6.0 K	Ohms
Output Resistance	4.0 K	5.0 K	6.0 K	Ohms
Overforce	–	–	4,500	grams

A disadvantage of VCR is that they can be used only when coupled with a device capable of providing positional feedback. In this case this shortcoming is countered by the use of the absolute encoder **A2** made by **US Digital** [8] No 22 on Fig. 5. This encoder is coupled directly to the shaft of the VCR which in addition to the high resolution of the encoder provides the exceptional accuracy of positioning of the gripper jaws.

The gripper jaws are easily interchangeable depending on the concrete process requirements and the type of the manipulated objects. The **FSS** sensor allows for the very accurate measurement of the gripping force in the wide working range of 0 to 1500 g and thanks to its linear characteristic – the convenient and easy transformation into DC voltage. Another important function of this sensor is to allow for the detection of the moment of contact between the gripper jaws and the manipulated object, as well as respectively the moment of the release of the object.

By means of racket 11 the gripper is coupled to the robot.

3.3. Operation of the device

The control of the device and its mode of operation is achieved by varying the value of the DC voltage supplied to the VCA coil and reading of the **A2** encoder and the FSS sensor outputs. Changing the polarity of the voltage supplied to the coil respectively opens and closes the gripper jaws. The speed with which the jaws are opened or closed depends on the magnitude of the supplied voltage. When establishing contact with the manipulated object (indication of which is provided by the measured output of the FSS sensor) the amount of applied gripping force is proportional to the supplied voltage as well. When operating with automatically oriented symmetrical objects the output value of the **A2** encoder provides accurate information for the dimension of the object between the two points of contact. If used in automated closed-loop mode this information can provide the deviation of an object dimension from it reference value. Rotating the gripper along its *Z* axis and performing several such touch measurements using the **A2** encoder can provide information about the object shape and/or provide deviation information along several measurement planes.

Increasing the applied gripping force (by increasing the voltage supplied to the VCA coil) and measuring the eventual change of the **A2** encoder output reading one can determine the hardness of the manipulated object, as well as to determine the optimal gripping force necessary for the subsequent manipulative operations to be performed on the object.

4. Conclusion

The presented specialized robot grippers with adjustable gripping force and limited capability for object identification is an attempt to offer some solutions that satisfy the complex requirements towards grippers designed for teleoperation and manipulation of small objects of various hardness. The developed devices are aimed for use in the following application areas: remotely operated groups of mobile agents (minirobots); measurements of object parameters and probe retrieval from the environment; manipulation tasks in biology as well as assembly operations; operations involving small and non-adhesive objects; and others. Experiments aimed to evaluate the design applicability and suitability for industry as well as research purposes are planned for the immediate future [10].

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Хваты нового типа для манипулирования маленькими объектами

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(Р е з ю м е)

В статье описываются разработанные специальные хваты для роботов с регулируемой силой захвата и с возможностями для идентификации объекта с приложением для работы с маленькими объектами и телеуправлением.