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Construction and controlling of the gripper for medical devices driven by shape memory alloy actuators

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CONSTRUCTION AND CONTROLLING OF THE GRIPPER FOR MEDICAL DEVICES DRIVEN BY SHAPE MEMORY ALLOY ACTUATORS

Introduction

In modern medicine the new materials are continuously introduced, as the needs for new features and parameters are in the high demand. The medical mechanical devices must be safe in use both for doctors and patients, they must be also precise, light and energy efficient. These requirements are fulfilled by Shape Memory Alloy (SMA) materials, which are more and more commonly used in advanced technics. They are characterized by a relatively large strain at high values of the generated stress[1].

In the case of medical robotics one of the most important issues is simplicity of the service by the user e.g. a surgeon. Moreover, the construction should try to minimalize the errors of the user like a hand shaking. For rehabilitation devices in turn the construction should be light, small in size and energy saving. That is why all mechanical elements responsible for movement which

[1] I. Dominik, *Advanced controlling of the prototype of SMA linear actuator*, "Diffusion and Defect Data – Solid State Data. Pt. B, Solid State Phenomena" 2011, Vol. 177.

consume significant amount of total energy should be considered particularly carefully.

1. Applications of SMA in medicine

The SMA materials are characterized by ability for different type of actions: superelasticity, one-way effect and two-way effect. In the one-way shape memory effect initial geometry appears during the heating, in contrast to the cooling where there is no shape change. The metal "remembers" only high temperature shape of the parent phase. In the two-way shape memory effect the alloys' shape behaves as if it remembers both the high temperature shape of the parent phase and the low temperature shape of the martensite phase. This two-way shape memory effect is connected with a cyclic process, which creates reversible changing of the sample, although the strain is lower than in one-way effect. In the research which is here presented one-way effect of the shape memory actuator was involved.

Nowadays a lot of researchers are looking for new industrial applications based on shape memory alloys. From the view of applicability of shape memory alloys one can distinguish several important groups such as: fixed electrical and mechanical connections (e.g.: in aerospace), temperature sensors (temperature protection), control systems (e.g.: heater), dumped vibration and noise systems and implants in medicine. Applying SMA wires, called also artificial muscles[2], give the possibility of creating advanced mobile robots, artificial limps[3], as well as other devices for medical purposes[4].

In medicine an interesting feature which open a wide area of application for SMA is constant temperature of a human body. It is possible to create

[2] A. Hadi, A. Yousefi-Koma, M. Elahinia, M. Moghaddam, A. Ghazavi, *A shape memory alloy spring-based actuator with stiffness and position controllability*, "Journal of Systems and Control Engineering" 2011, Vol. 225, No. 7, pp. 902-917.

[3] Z.W. Zhong, C.K. Yeong, *Development of a gripper using SMA wire*, "Sensors and Actuators", Elsevier 2006,Vol. 126, Iss. 2, pp. 375-381; Y. Shaoze, X. Feng, L. Xiajie, W. Jinhui, *A Gripper Actuated by a Pair of Differential SMA Springs*, "Journal of Intelligent Material Systems and Structures" May 2007, 18, pp. 459-466.

[4] J. Kwaśniewski, I. Dominik, *The SMA wires application in the Braille Monitor*, "Diffusion and Defect Data Solid State Phenomena" 2010, Vol. 165, pp. 290-293.

surgeon construction which are activated by contact with a body e.g. stents or surgeon clamps.

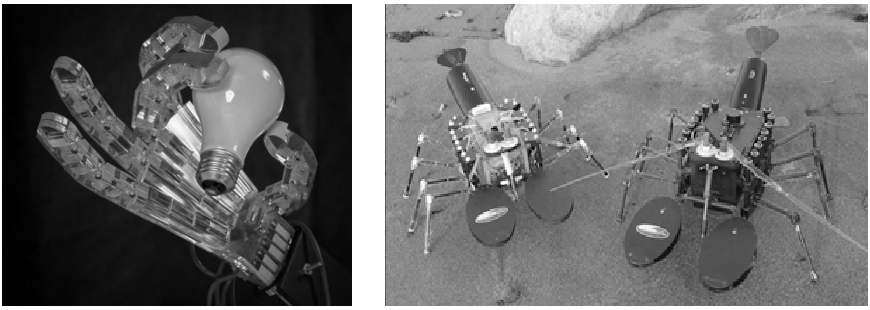


Fig. 1. Artificial hand and mobile robots driven by SMA wires

Source: http://www.engadget.com/2009/05/07/robotic-hand-controlled-by-compressed-air-grasps-the-concept-of/ (left); http://skitterbot.com/images/robolobsters.png (right).

Grippers which are a hand-shaped end actuators designed for seizing and holding are becoming more and more important in medicine, especially with the quick development of a technique called robotic surgery. The main idea is that a surgeon performs surgery using a computer which remotely controls very small instruments attached to a robot's gripper. One of the often used robotic surgical system is the da Vinci Surgical System which is designed to facilitate complex surgery using a minimally invasive approach. Up to date about 2,585 da Vinci Systems are installed in over 2,025 hospitals worldwide[5].

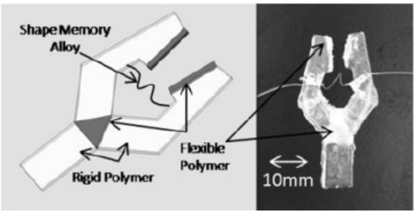
In the standard gripper construction either pneumatic or hydraulic actuators to achieve the gripping function are mostly used[6]. These actuators work reliably, but require a fluid such as air or oil. This fluid requirement makes these types of actuators difficult to adapt for use in medical applications because of surgical/hospital environment (high vacuum or high cleanliness applications). Additionally, pneumatic and hydraulic grippers are relatively expensive. Apart from the hydraulic/pneumatic grippers electro-mechanical

[5] http://www.intuitivesurgical.com/products/products_faq.html#18.

[6] G. J. Monkman, H. Schunk, *Robot Grippers*, Technology & Engineering 2007.

grippers are also used. In the case of electrically driven grippers lubricants or greases are required which is often problematic also because of required cleanliness.

The alternative, developed by many research centers, are gripping devices for gripping or grasping small medical elements of the surgery within a set of jaws utilizing a shape memory alloy material. Most of the constructions based on the SMA materials are made in micro and mini scale in which small SMA wires or springs are used e.g. at the Micro Robotics Lab at the University of Maryland[7] or the research center of the Memry Corporation[8].



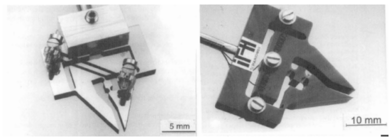


Fig. 2. Mini grippers driven by SMA springs
Source: J.E. Rajkowski, A.P. Gerratt, E.W. Schaler, S. Bergbreiter, *op. cit.* (left); http://memry.com/products-services (right).

However, only few gripper constructions based on SMA materials which can be apply for medical purposes are developed. The main disadvantages are the requirement of additional cooling system e.g. two finger gripper with extra cooling fans[9] or lengthening the SMA wire by its bending (no. 5 in fig. 3) to increase jaw opening which shorten the lifetime of a device[10].

[7] J.E. Rajkowski, A.P. Gerratt, E.W. Schaler, S. Bergbreiter, *A multi-material milli-robot prototyping process*, "Intelligent Robots and Systems" 2009, pp. 2777-2782.

[8] http://memry.com/products-services.

[9] Y. Shaoze, Y. Tianfu, L. Xiajie, W. Rencheng, *Tactile feedback control for a gripper driven by SMA springs*, AIP ADVANCES 2, 032134. 2012.

[10] U.S. Patent no. 4,900,078 Gripping device utilizing a shape memory alloy 1990, Inventor Bloch; J.T. Assignee: the Boeing Company.

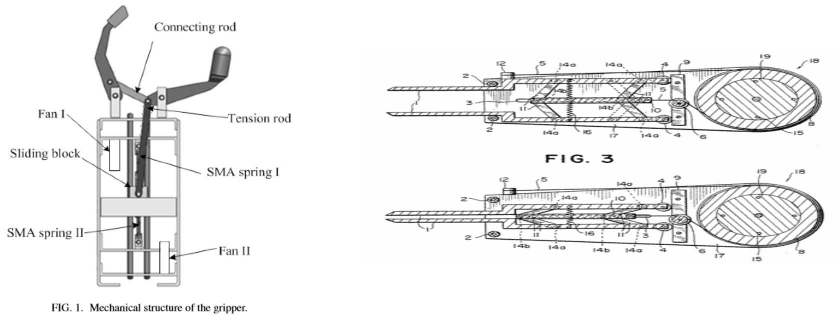


Fig. 3. Grippers driven by SMA elements

Source: Y. Shaoze, Y. Tianfu, L. Xiajie, W. Rencheng, *op. cit*. (left); U.S. Patent no. 4,900,078, *op. cit*.

2. SMA actuator used in construction

The main aim of the project presented in the article was to create the new contraction of the gripper for medical devices and medical robots which can grip objects in a range of centimeters. The used actuators produced by Miga Motors company are able to multiply the displacement which provides long strokes in small devices (fig. 4). In contrast to the presented gripper constructions the SMA wires are not bend (shortening the lifetime of a device) but are activated linearly (fig. 5). Additionally, the actuator housing allows SMA wires for quick heat dissipation so there is no need for an additional cooling system. In the gripper two actuators of the different construction were used: push DM0115PH and pull DM0115PL.

Fig. 4. Actuator DM series

Source: http://www.migamotors.com.

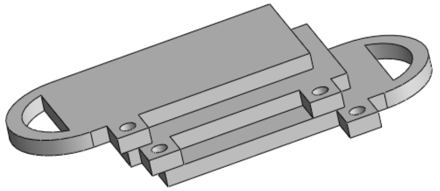


Fig. 5. The internal construction of the SMA actuator with linear activation of SMA wires

Source: own elaboration.

The internal structure of the actuator consist of moveable parts connected by SMA wires (fig. 5). The small diameter wires typically in the range 0.025÷0.5 mm are made of nickel-titanium. During heating the contraction of the wires is observed. The value of the contraction depends on the length of the wire because typical contraction equals 5% wire length. So, the longer the wire the more contraction can be observed. The contraction of heated wires is opposite to ordinary thermal expansion and in comparison it is larger by a hundredfold. The most user-friendly way of applying the heating is by using electrical current which flows through the wire.

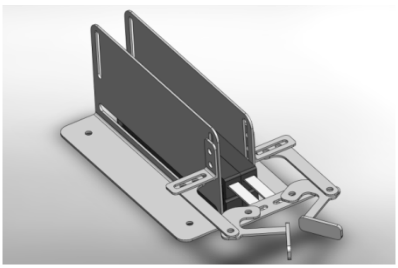
Because of the titanium SMA wires are really powerful, e.g. a wire with 0.2 mm in diameter can pull 0.6 kg. That is why SMA wires are characterized by one of the highest in technology weight ratio, which describes the ratio of a maximum external load to their own weight. It allows for building miniature devices which are extremely efficient. The main advantages of the actuator based on SMA wires besides the weight ratio are: silence, smooth motion and a really small size. A safe assumption is that any task requiring physical movement in a small space with low to moderate cycling speeds is something that most likely will be better done with actuator wires. Many of the tasks currently being done with small motors or solenoids can be done better and cheaper with SMA wires.

The actuator DM115 with its own weight 30 grams can create force equal 20N. In the construction two actuators were used. The first one created the one-way movement of pushing and the second one of pulling. Working together as an antagonistic pair they allowed fully control the movement in both directions: for closing and opening of the gripper. The actuators are electrically driven only during operating the gripper, which saves the energy.

The reason why the SMA actuators were used in the application is their exceptionally good cooperation with the medical devices and in surgery environment. The elimination of the vibrations is one of them. The used actuators are linear by design and most appropriate for linear motion, which can easy translate into movement of the gripper jaw. The creating movement based on the SMA wires placed in the actuators is very smooth and continuous. It increases the accuracy of the gripper positioning. In opposite to the classical devices e.g. motors there is no requirement for gearboxes and linkages and as result no lubricants or greases are used. The construction is entirely out of high strength engineering thermoplastics and stainless steel which is demanded for the high cleanliness applications. The last but not the least important feature of the actuators used in the medical applications is that actuator components are non-magnetic, and are even compatible with Magnetic Resonance Imaging (MRI) applications or other highly specialized diagnostic systems e.g. Positron Emission Tomography (PET).

3. Construction of the gripper

The base of the gripper was designed to ensure stability and possibility of fixing moveable parts. There are two parts which create a foundation and side walls. All elements of the gripper were made out of sheet metal 1mm thick (fig. 6).



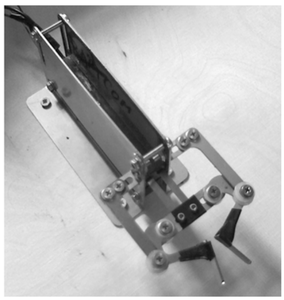


Fig. 6. 3D gripper project made in Solid Works and the real construction
Source: own elaboration.

The gripper size is depends on the actuators size which is 86 × 22 × 7,5 mm. The construction was optimized to restrict the size of the gripper. The diameters are presented in fig. 7.

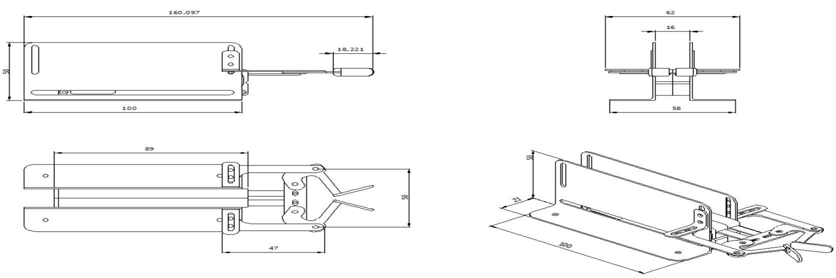


Fig. 7. The gripper diameters
Source: own elaboration.

The whole construction consist of 9 parts and it is symmetrical. The angle irons with arms were fixed to the one side walls. The linear movement of the actuators is transferred into rotary movement by a curved pivot jaws.

The construction was designed in Solid Works software. After drawing single parts the assembly project was built. Next the simulation of the movement was conducted which allowed any collisions to be located. In that way the accurate selection of the diameters of the single parts as well as modification of their shapes and joints location were performed. Finally the 12 mm stroke of the actuators allowed the gripper jaw to be opened in the range 0÷17 mm which is completely sufficient to grip and hold any small medical elements of the surgery set e.g. scalpel, surgical suture or surgeon's tourniquet.

The metal chosen for the construction has to be strictly selected because of the surgeon environment in which should operate. It should be biocompatible and resistant to corrosion. In the prototype version the stainless steel AISI 303 was chosen. Because of the material stiffness and high precision requirement the parts of the gripper were cut out by a CNC machine[11].

[11] R. Łuszczak, *Controlling of actuators with shape memory alloy used in medical devices, master thesis*, supervisor I. Dominik, AGH – University of Science and Technology 2011.

4. Controlling of the gripper

As it was mentioned to move the gripper an energy must be applied to the actuators which in the DM series electrical current is used. The first actuator DM0115PH model creates push movement an DM0115PL model pull movement – in that way the position of the gripper is controlled.

The internal resistance of the single actuator was 4.4 Ω. The 12V DC power supplied was chosen for safety reason. 1 A current value was the threshold value from which the actuator started moving. For the maximum 12 mm stroke of the actuator 1.3 A must be applied. However, the actuator worked quite slowly. Further current value increasing ended at 1.6 A value above which there was no faster actuator movement observed. Summarizing this part of the experiment 12 V DC voltage and 1.5 A current values gave the maximum speed of the actuator stroke which did not cause any damage. Next it was decided to use PWM controlling.

The duty factor should be about 60%, so the maximum current value in the high state was calculating from the formula:

$$PWM = \frac{I_{nom}}{I_{max}} \cdot 1{,}15 \cdot 100\% = \frac{1{,}5}{2{,}85} \cdot 1{,}15 \cdot 100\% = 60\% \tag{4.1}$$

where: – duty factor value, nominal current value, maximal current value.

The calculated maximum current value in the high state was 2,85A. The value seems to be high, however with 12 V power supply the energy consumption is still acceptable.

The position of the gripper was controlled directly by DAQ measurement cards made by National Instruments. The first model NI 9263 was analog output card working as a generator in the range 0÷10V and second model NI 9215 was analog input card with signals range 0 ÷ +/-10V. The SMA actuators needed over 2 A current for activation so the additional electronic circuit was built. It was decided to use NPN transistors for amplifying the output signal of the DAQ card. The problem was to low value of the gain (maximum 40dB). Taking into account that maximum current generated by the card was 1 mA the maximum amplified signal was 100mA, so it was too low. The solution was to use a Darlington Pair (BDW42) which can amplify signal even a few thousand times which was sufficient for the task.

Having solved the problem of power supply the next step was to measure the current value flowing through the actuator. To fulfill the task a special standard ceramic resistor with 1Ω value was connected in series to the actuator. The voltage drop value on the resistor is directly the value of the current in the circuit.

The voltage drop on the actuator can be calculated from the formula:

$$V_{actuator} = V_{base} - 2 \cdot V_{Si} \cdot \frac{R_{actuator}}{R_{actuator} + R_{resistor}} \quad V \tag{4.2}$$

where: voltage drop on the actuator, voltage between Darlington base and circuit ground, voltage drop between base and emitter of transistor, actuator resistance, standard resistor resistance.

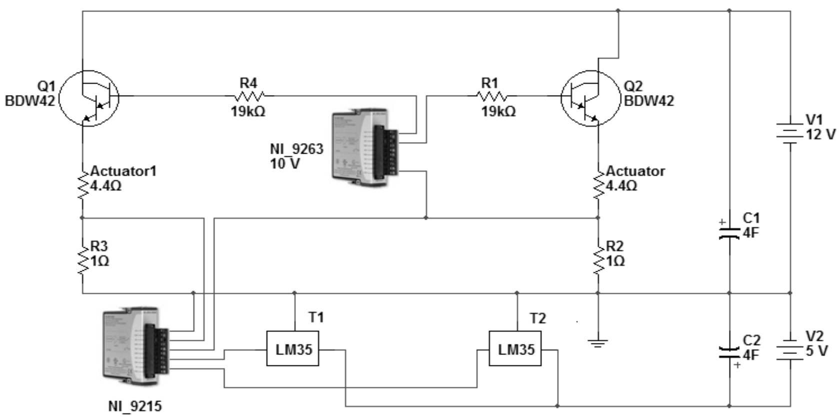


Fig. 8. Control circuit of SMA actuators
Source: own elaboration.

During testing the circuit presented in fig. 8 it was observed that during longer periods of feeding the actuators the Darlington Pair increased its temperature. To ensure the safety of the circuit additional two temperature measurement chips LM35 were fixed to the transistor drains made of metal.

The output signal of the chip is calibrated in such a way that 10 mV indicates 1 °C, which means that the value 0.214 V equals 21.4 °C. For protection against any unstable states in the circuit which may influence the measurements the 4,7 μF capacitors were connected parallel to the power source.

5. Controlling application

The controlling application was created in LabView software made by National Instrument which is a commonly used in controlling and measurements area. From the beginning it was decided to build the multithread application, where different events have different priorities. The firs thread was connected with a reliable user interface. The delay time between pressing the buttons and the device reaction was assumed to be shorter than 10 ms, which is about ten times faster than reaction time of the user. Moreover the indicators and control switches of the interface have to be placed logically and friendly for a user.

The second thread was responsible for sending data to the output card. The task was to not overload the system resources and avoid losing data. Similarly the third thread was created to cooperate with the inputs signals. The buffering operation was required as well as decoding received data. Not all data gathered by the third thread were presented to the user in the interface (the first thread), there was no need because with a higher sampling time a user could not see any difference, the visible plots were just for orientation while the full data were saved on a disc.

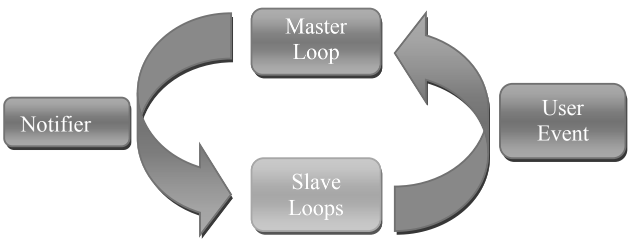


Fig. 9. Data flow between program events
Source: own elaboration.

According to the described above assumptions each of the threads must have been realized in the separate loop. The first thread responsible for running the interface was chosen for the master loop. The loop was created with an event structure often called an interruption structure. Depending on the event which occur in the interface e.g. a button pressing the structure will run an appropriate minor event. In the case of starting a new event while the previous one is running the queuing operation is executed. The data flow between program events are presented in fig. 9.

The threads responsible for servicing the measurement cards were located in two other loops. In the structure they are considered as slave loops. The used environment allows many threads to be executed parallel. Additionally modern CPUs are constructed as multicore with hyper-treading feature, which significantly decrease the cycle time of the program. To reach the maximum program efficiency minimum three core CPU is required. In the case of two core processor it is recommended to assign the master loop for one core and the slave loops for the second.

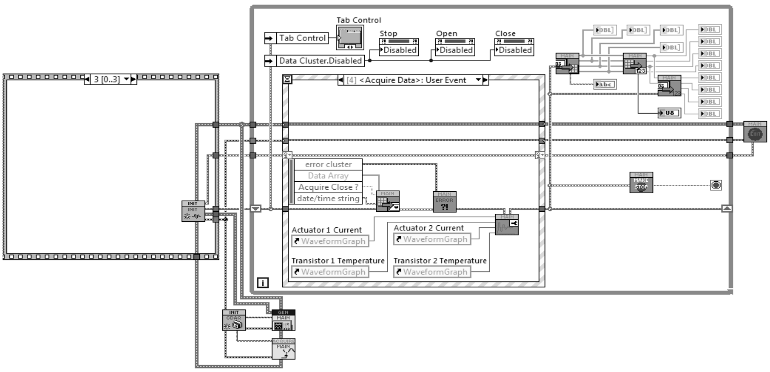


Fig. 10. The main program of the implemented in LabView application
Source: own elaboration.

The communication between the master loop and the slaves loops was realized by synchronic operation “Notifier”. In that way both slave loops received the same data bunch and after processing it they are waiting for a next bunch. This structure caused no data loss. The return transmission from the slave loops to the master one is controlled by “User Event” structure. The transmission is realized by an event structure together with dynamic events. Every user event is registered by the event structure. Sending the bunch to the master loop led to execute the appropriate event in it. The architecture does not allow slave loops to communicate between each other. The communication from the one slave loop must be sent to the master loop via user event and after verification via notifier is send finally to the second slave loop. Thus the used architecture prevent a bunch of circulating between the slave loops when an errors occur.

The structure of the implemented in application consist of the main program (fig. 10) and 22 subprograms e.g. Init, Gen Loop, Acquire Loop or errors handling (fig. 12).

The interface of the program “Manipulator Control Application” was created to maximize the simplicity (too many options are often difficult to work with) with the full functionality (fig. 11).

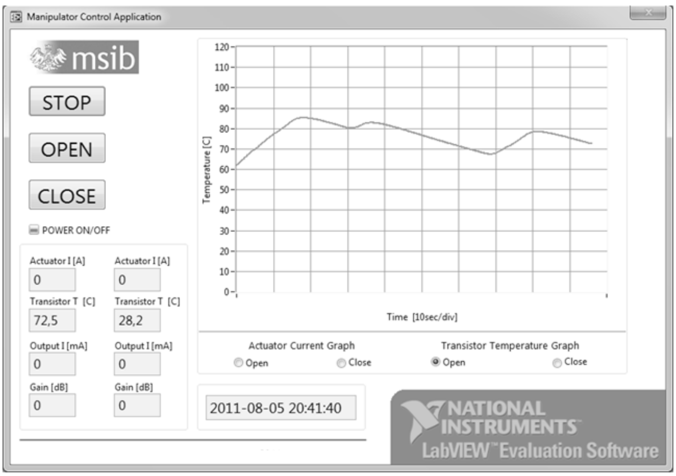


Fig. 11. The interface of the program „Manipulator Control Application”

The three most important switches are “STOP” which closes the application while “OPEN” and “CLOSE” operate the gripper adequately. The indicator “Power ON/OFF” shows whether the power supply is connected or not. At the left bottom side a section with measured signals values is placed. Two data columns match two actuators, where for each of the actuator the current value flowing through the actuator, the temperature of the Darlington Pair, current output of the DAQ card and gain of the Darlington are presented. The main part of the window presents a graph where four different plots may be presented. The selection of the plot is available below the graph: Actuator Current Graph and Transistor Temperature Graph both of them available for opened and closed jaws action.

Apart from the events controlled by a user from the interface panel the program operates also with dynamic events. The error arising activates a subprogram “Error” which displays an error message (fig. 12). In the pop-up error window short information about the type of the error is shown as well as its code number.

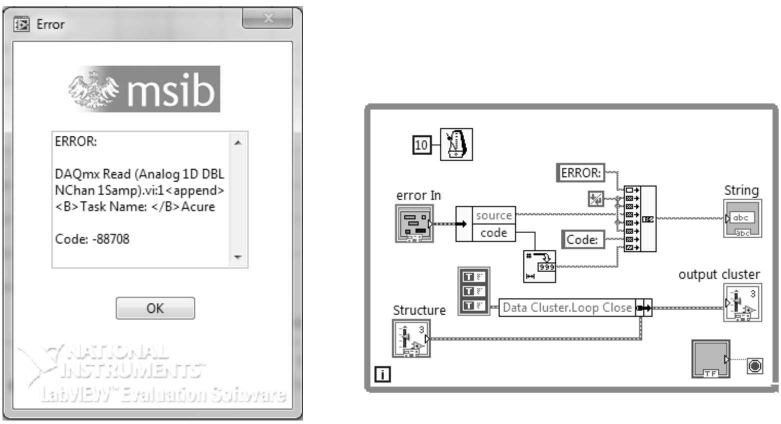


Fig. 12. Error message and its source code (one of the 22 subprograms)

If the error occurs in any of the slave loops it will close this loop and send the information to the master loop. Otherwise if the error occurs in the master loop the three variable responsible for closing all three loops are activated.

Summary

In the article the prototype construction of the gripper for medical devices was presented. The main advantage of the new solution is exchanging the traditional drive e.g. an electrical motor for SMA actuator. The main advantage of the SMA actuators is their weight ratio, one of the highest in modern technics. In the case of used actuator which weights 30 grams force equal 20N can be created. Other advantages especially important in surgeon environment are: silence, smooth motion and a small size. What is more actuator components are non-magnetic, and are compatible with Magnetic Resonance Imaging (MRI) applications or other highly specialized diagnostic systems e.g. Positron Emission Tomography (PET).

The gripper controlling was realized by created application which allowed for simple manual controlling of the jaws as well as observing the crucial values in the system e.g. current and temperature. Currently the research on controlling accurately the jaws position and the gripping force are in progress. The precise distance and force sensors were already installed.

The application for controlling the gripper jaws was built not as a simple serial executed source code but as the multithread program. It was prepared for further development where the cycle time of the application is crucial e.g. force controlling of the gripper holding an object.

The built prototype is the first step in creating the whole series of the SMA grippers. The size and force of the gripper is determined by used SMA actuator. Nowadays the actuators are available in wide variety of size from a few millimeters to decimeters and force up to 70 N (with own 30 grams weight).

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U.S. Patent no. 4,900,078 Gripping device utilizing a shape memory alloy 1990. Inventor Bloch; J.T. Assignee: the Boeing Company.

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KONSTRUKCJA CHWYTAKA MEDYCZNEGO WYKORZYSTUJĄCEGO SIŁOWNIKI Z PAMIĘCIĄ KSZTAŁTU I STEROWANIE NIM

Streszczenie

W artykule przedstawiono nowy typ konstrukcji chwytaka medycznego dla urządzeń i robotów medycznych. Tradycyjny aktuator, tj. silnik elektryczny, został zastąpiony przez aktuator (siłownik) zbudowany ze stopu z pamięcią kształtu (SMA). Zastosowany komercyjny typ siłownika wyprodukowany przez firmę Miga Motors zdolny jest do zwielokrotnienia przemieszczenia elementu SMA, co pozwala na wydłużenie zasięgu wysuwu siłownika przy pozostawieniu zwartej obudowy. Aktuator potrzebuje energii tylko podczas operacji zamknięcia i otwarcia szczęk, dzięki czemu jest energooszczędny. Wysuw siłownika o długości 12 mm pozwala na chwytanie niedużych elementów chirurgicznych, np. skalpela, nici chirurgicznej lub pensety anatomicznej. Podczas projektowania konstrukcji wykorzystano oprogramowanie Solid Works, a samo kontrolowanie położenia chwytaka zrealizowano, stosując oprogramowanie LabView.

Tłumaczenie Ireneusz Dominik