The Control of Smart Material based Actuators for Industrial Robots

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***Abstract*—This paper describes the use of smart materials and adaptronic control concepts in small size robots. Small size in this specific research means that robot hand have the span from several centimeters to some tens of centimeters. The possibility of building robot mechanics using different kind of smart materials are analyzed. There is no target to build the specific robot, but the possible solutions are analyzed. The control method for SMA (Shape Memory Alloy) actuator is proposed. The method for estimating temperature inside the SMA sample is described. The experimental setup is built up and the test measurements are made. The dynamics of control and the energy consumption of proposed control method are analyzed.**

Keywords*—Smart materials, robotic, actators, shape memory alloy, temperature control.

I. Introduction

The Robots are widely used in modern industrial manufacturing. The robot size and performance could be very different depending on specific application. Some robots are moving grams but others tons of load. There are “conventional” motors or actuators for driving robots. With the conventional actuators usually consider the electrical, pneumatic and hydraulic drives. For large power drives the electrical and hydraulic actuators are preferred because the pneumatics energy efficiency is lower. The electrical drives could be of very different design: linear and rotational, asynchronous, DC motors and step motors. For smaller applications also solenoids and voice coils could be used. Even electrostatic motors could be used. Commonly electrostatic motors are used in micro and nanotechnologies [5], but some companies are started to produce high power electrostatic motors with power in the power range of hundreds of Watts [6].

Miniature pneumatics cylinders are available with external diameters starting from 4mm and strokes in range 5mm to 25mm [2]. The miniature hydraulic motors and cylinders also are available [3], [4].

All these actuators are commonly used for solving different tasks in industrial robotics and machinery. Each type of actuators have advantages in some applications. The actuators based on the smart materials also have specific features that can be favorable for the solutions of industrial tasks. The piezoelectric actuators are widely used in modern machining. Typical application is vibration associated machining and fast tool servos. There are different smart material types with very different specifications. Comparing to the “classic” actuators the smart material actuators could be faster, cheaper, simpler, smaller and so on.

II. Current use of smart material actuators

In the several last decades the use of Smart Materials are more and more popular for building of actuators [1]. The smart materials are already commonly used in robot grippers and tools. There are some toy robots made with smart material based actuators, but not industrial robots. The most common Smart Materials are listed in the TABLE I.

TABLE I. MAIN PROPERTIES OS SMART MATERIAL ACTUATORS.

Material type	Stimulus	Response
Piezoelectric	Electric Field	Mechanical Strain
Electrostrictors	Electric Field	Mechanical Strain
Magnetostrictors	Magnetic Field	Mechanical Strain
Shape Memory Alloys	Temperature Change	Mechanical Strain
Electroactive Polymers	Electric Field	Mechanical Strain
Electrorheological Fluids	Electric Field	Viscosity Change
Magnetorheological Fluids	Magnetic Field	Viscosity Change

The Smart Materials differ also by its reaction time, forces, strain and other properties [7], [8], [9] [10]. Electrorheological and Magnetorheological fluids change their viscosity and can’t be directly used as actuators, but they are used in control of vibrations or building mechanical couplings and brakes. The fast reversing of rotation also is possible by use of couplings based on these fluids.

Piezoelectric actuators nowadays are used in many fields. The main disadvantage of piezoelectric material in building robot actuator is the small strain – only 0.1%. That mean if 1m long actuator of this material were built the displacement of the end will be only 1mm. The levers and special mechanical constructions could be used to amplify the displacement. But 10 fold amplification is the rational limit. The other direction in

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piezoelectric actuators is various motor constructions. These motors work similar as electric step motors. Linear and rotational motors are available from stock with the nanometer resolution. These motors could be used as robot actuators but they are expensive. Very similar properties to piezoelectric have magnetostrictive actuators, but they are mostly designed for generation of vibrations and have the same small travel range. There are only patents and some prototype for magnetostrictive motors, but their characteristics isn't outstanding

Shape Memory Alloy (SMA) actuators are widely used in industry. SMA wire actuator have strain up to 5%, but SMA spring up to 50% what is the same value as human muscle have. Using SMA actuator for the robot building is very convenient Fig. 1.

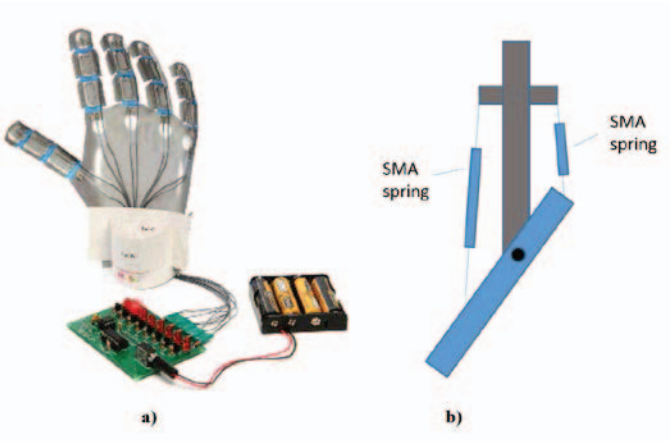

Fig. 1. Robotic hand toy a), SMA spring based robottic arm joint b).

The SMA material properties are changed by the change of material temperature. SMA actuators commonly are used to their end limit positions, but proportional control also is possible. The external positional sensor or selfsensing by the resistance change of the SMA material is possible. Various control techniques are discussed in literature: PID, Fuzzy, Model based, feed-forward etc. Sensorless position control can work with the errors from 1 to 3%. The 1% error could be adequate for same robotics applications. The direct heating of SMA by electric current or indirect heating is possible (Hot air, water etc.). The SMA based actuators are one of the strongest. The Nitinol SMA nominal tensile stress is 172MPa [12]. That's mean that 1mm^2 wire could produce force equal to 127N. Let's consider the strip of SMA with cross section 40x1mm. Then the produced force will be 40 fold larger and reaches the 6880N or 702kg. This force could be used for same cutting or could be used to get larger displacements by some mechanical lever system.

The heating of such SMA sheet by electric current will not be the easy task. The considerable current will be required. Let's make some calculations for the proposed SMA strip with the 40mm length. The electrical resistance of Dynalloy SMA is 100μΩ·cm resulting in the resistance of the sample equal to 1mΩ. To keep the SMA sample at the required 80°C for actuating the approximately 1.5W power is required [11]. By the Ohms law that power require 38.7mV voltage and 38,7A current. These are the values for static regime. To heat the SMA sample the mass and specific heat of the material should be considered. The required heat energy could be calculated by the formula (1)

$$Q = c \cdot m \cdot \Delta T \tag{1}$$

Where the Q – required heat energy, J

c – specific heat of SMA material, J/kg·K

m – mass of SMA sample, kg

ΔT – Temperature difference, K

The specific heat of SMA material is 838 J/kg·K. The mass can be calculated by geometric dimensions and density which is equal to 6450kg/m^2. The calculated mass is 10.32g. The temperature difference is the necessary temperature change required to change SMA material from Martensite to Austenite mode and. For the selected Dynalloy SMA sample the Martensite temperature are 50°C and Austenite temperature is 80°C resulting in ΔT=30°C. Using these values by the equation (1) the result is 259.4J. If the required time for heating would be the 1sec then the necessary heating power is equal to 259.4W. To provide such heating power the 0.51V and 509.3A is required. The power source with such parameters could be constructed but providing of high efficiency is not an easy task. Also the power connection wire cross section must be carefully selected. The fast cooling also would be hard to realize. The dynamic control of SMA material actuator consists of successive heating and cooling cycles. The efficiency of SMA actuators is low somewhere about 4%. So the nearly the same heat energy will flow to and from the SMA sample. For this task the heat pump seems to be well suited.

III. SMA TEMPERATURE CONTROL BY PELTIER ELEMENTS.

As stated in the previous section the heating of defined SMA sample by electric current isn't very convenient and heat energy pumping could be available. The semiconductor heat pumping unit the Peltier element could be used for heating and cooling of SMA strip as shown in the Fig. 2.

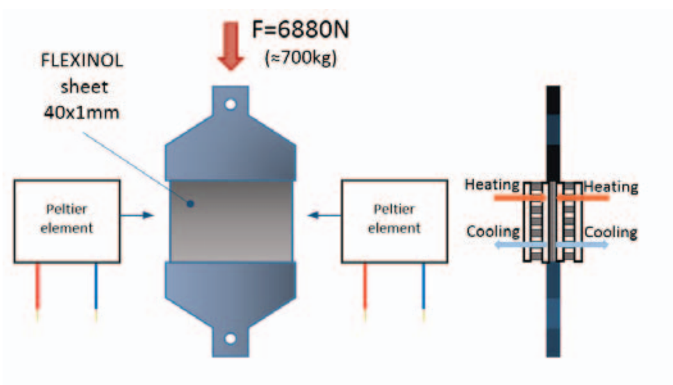

Fig. 2. Proposed Indirect Heating method of SMA actuator.

In this configuration the two identical Peltier elements are used. The Peltier elements usually are used for cooling but their functionality could be reversed for heating also. The Peltier elements are placed directly to the SMA strip with the minimal gap possible. If necessary the some thermally conductive substance could be used in the gap to provide the better heat energy transfer. The coefficient of performance (COP) for Peltier elements could reach the 4 for the zero temperature difference and will drop to about 1 at the required 30°C temperature difference. The one side of Peltier element is at the SMA strip but other should exchange the heat energy in the necessary direction with the environment. In the Fig. 2 the other sides is left open to the air. In reality the some kind of heatsink would be required.

IV. EXPERIMENTAL SETUP

The experimental setup are designed to measure the heating and cooling processes of SMA strip. The SMA material strip is expensive and before the tests there is hard to guess the optimal dimensions. So for the thermal tests the equivalent steel plate is used. The steel sample have approximately the same physical properties (density, specific heat, thermal conductivity) that affect the cooling and heating processes as Dynalloy shape memory alloy [12]. When heating and cooling the SMA plate by the method described earlier the slowest temperature change will be in the midpoint of plate thickness. Directly measure the temperature inside the sample plate is impossible Fig. 3.a. If the Thermal flow from both sides of the SMA plate are equivalent then in in the midpoint of the SMA plate (axis of symmetry) the heat exchange will be zero Fig. 3.b. Then if looking from the left side of SMA plate the thermal flux at the axis of symmetry is zero and could be replaced by thermal insulator Fig. 3.c. In this case the temperature measurement point is on the surface of SMA plate.

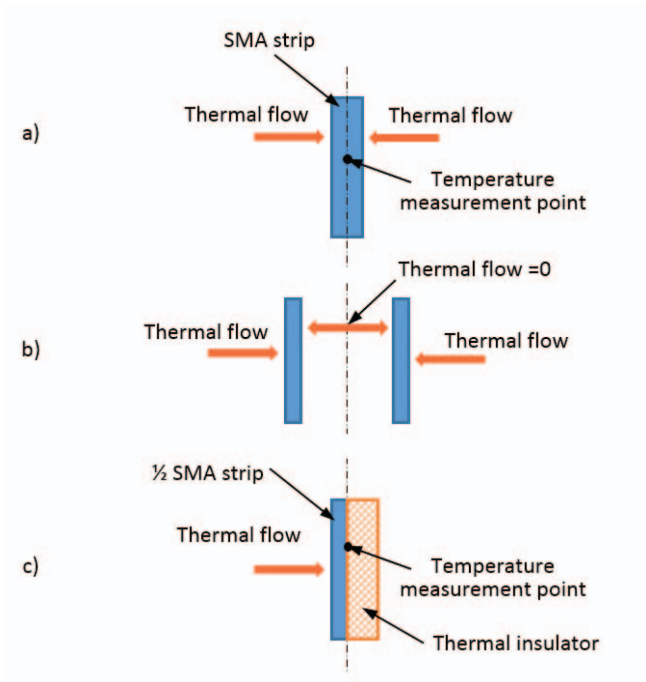

Fig. 3. Substitution scheme for midpoint temperature measurement.

The experimental setup construction is shown on Fig. 4. The aluminum base is a massive heatsink the mean temperature of which is kept constant. The heatsink also have fins not shown in the picture. The Peltier element is mounted on the aluminum base by the use thermo-conductive paste. SMA sample (steel in actual construction) are simply placed on the Peltier element. The both surfaces are smooth and level so the gap between them is minimal. The SMA sample is lightly pressed to the Peltier element by the means of soft thermal isolator. The temperature sensor is mounted onto the SMA sample by thermo-conductive paste. The used temperature sensor is miniature in size and with fast response. The full response time (90%) of the temperature sensor is 0.4 seconds [13].

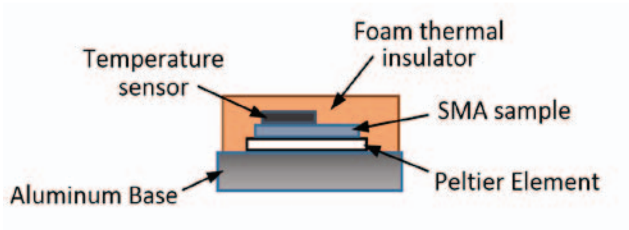

Fig. 4. Experimental.setup construction.

The small control system with PLC and SCADA is assembled to control the temperature of SMA sample.

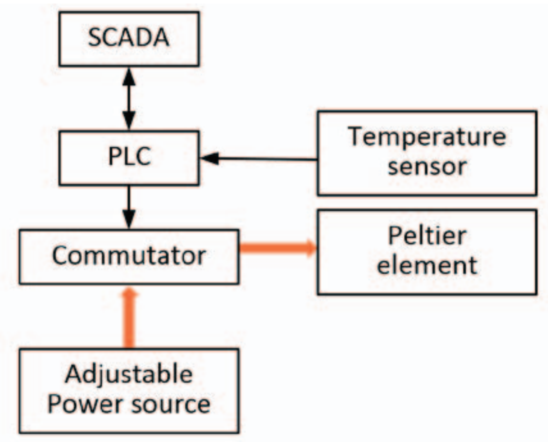

Fig. 5. Temperature Control System.

The constant voltage mode is selected for the Adjustable Power source. This mode is safer for the operation of Peltier Element. In the constant current mode the voltage can easily exceed the maximum allowable voltage [14]. The PLC controls the Commutator to provide 3 modes of operation of the Peltier element:

- Heating
- Cooling
- Idle/Off

The temperature of SMA sample and the operating mode of Peltier element are recorded in the simple SCADA application. The temperature of the aluminum base is not constantly measured and recorded. The temperature of aluminum base is manually monitored by infrared temperature sensor and or by the SMA temperature sensor if Idle/Off mode is selected for Peltier element. The simple program is written for the PLC to control the temperature of SMA sample in such a way that when heated up to austenite phase temperature the cooling mode is selected and when cooled down to Martensite phase the heating mode is selected. This test allows estimate the maximum operation speed of SMA actuator.

The main part of experimental setup is shown in Fig.7. The Power source, relay based power commutator and the aluminum base/cooler with mounted elements are showed. The aluminum peace on the top of the thermal insulator is not involved in the tests this element only works as additional weight to keep the thermal insulator in place. The PLC that controls the heating/cooling processes and computer with running SCADA software aren’t shown in the photo.

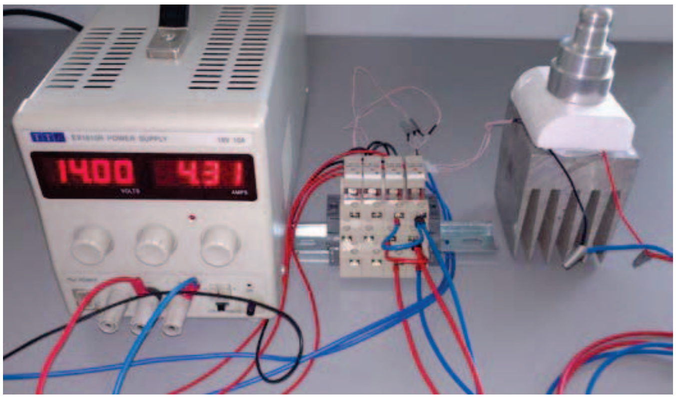

Fig. 6. Experimental setup photo.

V. MEASUREMENTS AND REZULTS

The thermal inertia of Aluminum base are high relative to Peltier Element. The Aluminum base temperature should be properly chosen to provide the optimal temperature regime for tests. As mentioned before for operating of the SMA actuator the temperature change is needed between Austenite and Martensite temperatures. For the low temperature Flexinol grade SMA the required temperatures are 80°C and 50°C [12] as shown in the Fig. 8. The one logical choice for the Base temperature could be at the exact midpoint between these temperatures Tbase=(80+50)/2=65°C. But Heating process in Peltier element are much powerful than cooling, because in heating not only the heat pumping but also the resistive heating takes place [14]. Then maybe the common room temperature 25°C should be chosen. This version requires additional cooling because in the both the Heating and Cooling processes energy will be consumed and the Base temperature tends to rise and it’s impossible to cool down to room temperature using only room temperature air flow. The second argument against this selected temperature is fact that for heating of SMA sample to 80°C the high temperature difference of 55°C is required and also high heating energy will be required. After making such decisions and some simple tests the temperature for Aluminum Base was chosen equal to 40°C.

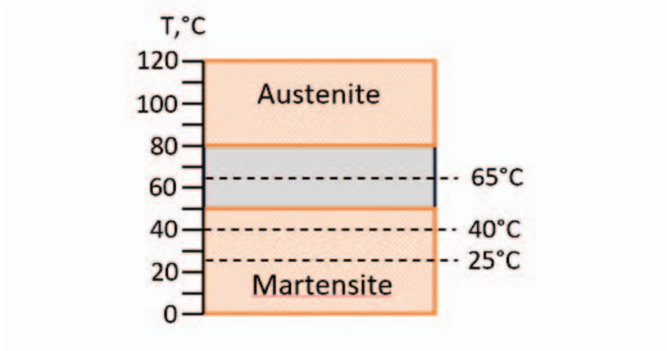

Fig. 7. Aluminum Base temperature selection.

The several tests are made to estimate the dynamics of the temperature change of the SMA sample. As mentioned previously the Aluminum Base temperature was selected equal to 40°C. The Power source is adjusted to provide constant voltage equal to 14V. This voltage is safe for the selected Peltier element and also provides the Heating/Cooling capacities close to the maximum available [14]. For the Cooling process this voltage could be applied continuously, but for heating especially with heated side thermally insulated the maximum temperature should be monitored and the heating process must be terminated before reaching maximal allowed temperature Fig. 9.

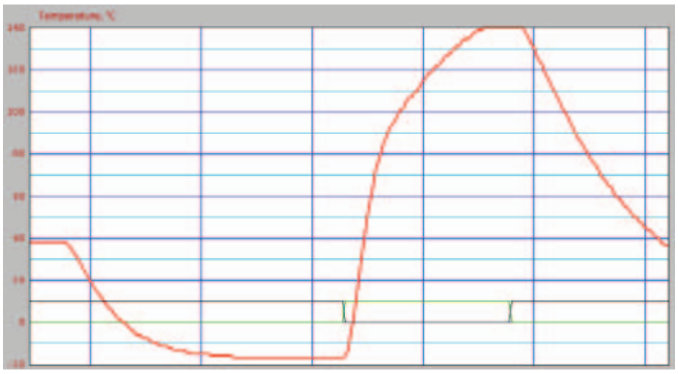

Fig. 8. Heating/Cooling curves with 14V power source.

The temperature change of Peltier element is relatively slow, but for SMA actuator the full span isn’t needed the only 30°C temperature difference is required. Testing the dynamics by automatic Heat/Cool cycles the following curve are recorded Fig. 9. From this curve follows that the heating and cooling times is approximately equal and takes 2.6sec. This is the temperature change test on the surface of Peltier element.

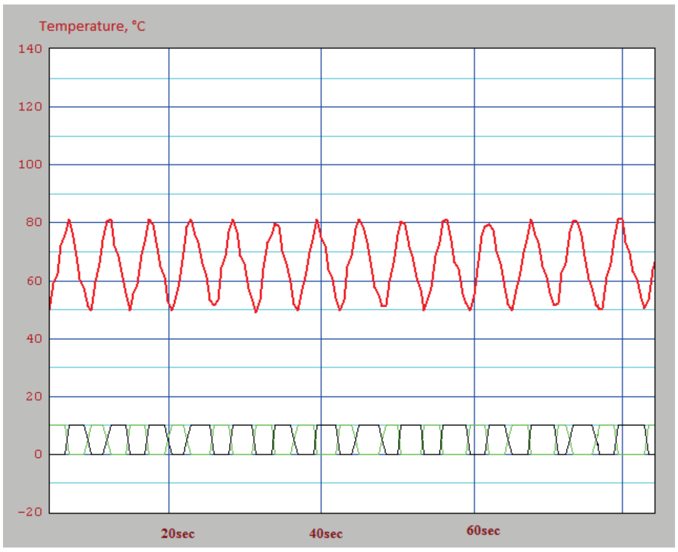

Fig. 9. Temperature cycling on the surface on Peltier element

Several tests are made with different SMA substitutive samples. The Copper and Steel materials are used. The thin Copper foil 0.005mm have the same time as Peltier Element itself, the 0.2mm Copper foil have 3.3sec and 0.4mm steel sheet have 3.6sec (Fig. 10) of time to cycle the temperature.

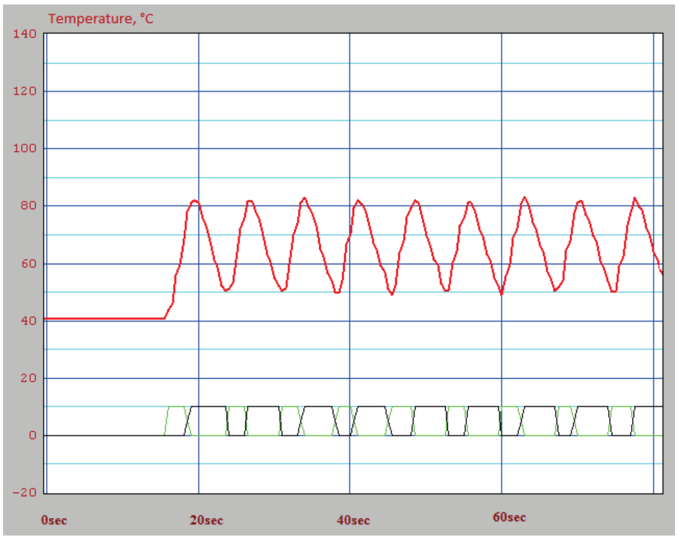

Fig. 10. Temperature cycling on the 0.4mm thich Steel plate surface

The main fraction of time requires the Peltier Element itself. This timing could not be improved. There is of course the possibility to get faster temperature change but then the different high performance Peltier element must be used. There are available the more powerful Peltier element with the same external dimensions with the more than three-fold Heat pumping power capabilities 280W instead of 75W [14], [15]. Then the temperature change time of SMA sample possibly could be improved from 3.6sec to 1sec. This time also isn't fast enough for example for part packaging or conveyors, but could satisfy some slow applications like workpiece clamping or for loading/unloading the metal treatment machine work cells.

The energetic properties of proposed method isn't very exciting. The keeping the SMA sample at Austenite temperature 80°C would require the 7.83W (5.4V and 1.45A) with selected base temperature equal to 40°C. The higher base temperature would be preferable for this operating mode but then again the dynamic properties will be worse because of longer cooling time. With the selected base temperature the keeping SMA sample at the Martensite temperature 50°C will not require energy at all. If the high temperature phase is necessary for longer periods then the base temperature could be adequately adjusted for that period to keep the energy consumption lower. In any case seems that the direct electric heating requiring only 1.5W of energy could be more energy effective.

VI. Heat Transfer Estimation

In the performed experiments the tested material sample is lightly pressed to the Peltier Element. As a result the small air gap is created between the two surfaces. Both surfaces are smooth and the gap is minimal. There aren't made tests or measurements how big is the gap and its influence to heat transfer, but some calculations are made. The air convection in small gap is negligible. The radiation heat exchange also is small, but simple estimation could be made. The maximum heat exchange occurs if the surfaces are absolute black. This is not true in this case but gives the value for consideration. In the case of black surfaces the heat transfer can be calculated by formula:

$$q = \sigma \cdot A \cdot (T_h^4 - T_l^4) \qquad (2)$$

Where the q-power of heat transfer, W

A-Surface area, m^2

T_h-High side temperature, K

T_l-Low side temperature, K

σ - Stefan-Boltzmann constant, 5.67 * 10^{-8} $W/m^2 \cdot K^4$

Choosing the maximum heating case when the heater temperature is 140°C and the heating surface temperature is 40°C by the formula (2):

$q=5.67* 10^{-8}*0.04^2*((140+273)^4-(273+40)^4) =1.77W$

This is a tiny power in respect to the 70W of Peltier element and in reality the surfaces aren't absolute black and the temperature difference will drop so the radiant heat transfer will be significantly less.

More important is calculate the heat transfer by conduction. In the experiments the gap is small and filled with air. If the surfaces is not smooth the gap will be larger and also some friction will arise. In this case the gap could be filled by oil to improve heat transfer and to reduce the friction.

To make calculations of acceptable gap size the limit conditions must be defined. The maximum heat pump power of used Peltier element is 70W but that will be true only in the case of zero temperature difference. Let assume that acceptable conditions will be the temperature drop across the gap equal to 20°C in the case of transferred heat power equal to 50W. The power of heat transfer can by calculated by the formula:

$$q = \frac{k \cdot A \cdot \Delta T}{d} \quad (3)$$

Where q-power of heat transfer, W

K – thermal conduction coefficient, W/m·K

A – surface area, m^2

ΔT – temperature difference, K

d – distance between surfaces, m

To get the acceptable size of gap between the surfaces the formula (3) must be transformed:

$$d = \frac{q}{k \cdot A \cdot \Delta T} \quad (4)$$

In the case of air gap the result using formula (4) is:

D= $50/(0.025*0.04^2*20)$=0.016mm.

The calculations are repeated for different gap filled media and the results are written in the TABLE II. The Galinstan is the trade name of Gallium based metal alloy that stays liquid in the room temperature.

TABLE II. ACCEPTABLE GAP SIZES FOR DIFFERENT SUBSTANCES

Gap filled media	Thermal conductivity, W/m*K	Acceptable gap size, mm
Air	0.025	0.016
Oil	0.15	0.096
Water	0.6	0.38
Galinstan	16.5	10.5

Of course these gap sizes are acceptable in respect to thermal conductivity. The calculated gaps for water and especially Galinstan could be too big if taking in account the specific heat of filled media that will slow the heating process. But the gap sizes up to 0.2-0.5mm could be acceptable. In the static regime of course the calculated values are valid.

VII. CONCLUSIONS

Several smart materials are suitable for miniature robot actuators. There are some applications where the SMA alloy based actuators could successfully replace some of “conventional” actuators such as solenoids, pneumatic, hydraulic and electric with gear trains. The proposed control of SMA actuator by Peltier element could be competitive to direct heating by electric current but not an energy efficient solution. The response time of the SMA based actuator is relatively slow but could be improved by properly chosen elements. Lot of researches and especially experimental work must be accomplished to find the optimal solution. There are some other smart material based actuators that should be studied.

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