ANNUAL JOURNAL OF ELECTRONICS, 2009, ISSN 1313-1842

Control System for High-Precision Thermal Actuation

Jeroen P. van Schieveen, Ruimin Yang, Stoyan Nihtianov Nihtianov and Jo W. Spronck

Abstract – **Many applications in high-precision equipment require the alignment of different parts at the sub-micrometer level. For this purpose, a new compact and robust thermally-actuated alignment device, called the "thermal stepper", has recently been proposed [1]. This article presents an electronic control system for this thermal actuator. The electronic control system has been designed as a part of a multi-disciplinary project. It enables a faster and a more accurate control of the thermal actuator, extending its range of applications. The article covers the design of the system, the simulation results and the realized setup. The measurement results show the benefits of the new controller.**

Keywords – **Thermal stepper, auto-aligment, electronic control system**

I. Introduction

Many high-precision systems rely on very accurate positioning and alignment of multiple parts. Examples of these systems are optical instruments, such as microscopes, lithographic tools, or satellites. The required positioning accuracy is often in the sub-micrometer range. The required position stability is even more stringent and can be in the sub-nanometer range.

There are different ways this accuracy can be achieved. In some cases, it is possible to machine all relevant parts with very small tolerances. Usually this increases their price significantly. Another option is to align the parts manually, with or without special alignment mechanisms. In both cases the procedure is time-consuming and requires all parts to be accessible.

A new remotely-operated alignment mechanism has been designed that can be used in an inaccessible environment [1]. It can successfully replace normal manual alignment tools. It also reduces the total alignment costs by reducing the hands-on setup time. The simple structure of the alignment mechanism, which consists of only two main parts, guarantees a very stable behavior after installation and alignment.

The base of the system is a monolithic structure, which is connected to the moving object by at least three clamping elements. Sequential heating of the clamping elements enables a displacement of the moving object. In contrast to common thermal actuators, the object remains in the displaced position even after all the elements have cooled down to their initial temperature. Fig.1 shows a possible configuration of the thermal actuator system.

J.P.van.Schieveen and J.W.Spronck are with the Department of Precision and Microsystem Engineering, Faculty of 3mE, Delft University of Technology, Mekelweg 2,2628CD Delft, Netherlands. e-mail: J.P.vanSchieveen@tudelft.nl,

R.Yang and S.Nihtianov are with the Department of Microelectronics, Faculty of Electrical Engineering, Delft University of Technology, Mekelweg 4,2628 CD Delft, Netherlands. e-mail: R.yang@student.tudelft.nl,

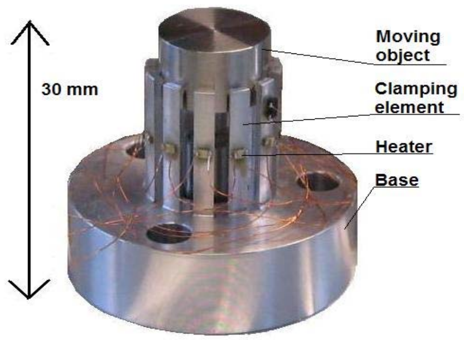

Fig. 1. Image of the basic thermal stepper system.

Sequential heating and cooling of the elements is controlled by an electronic system. This type of system can be open-loop, consisting of a microcontroller and power switches that switch the current to the heaters on the actuation elements. Besides this the control can also be done by a closed-loop system, which also needs a temperature measurement for every element.

In this paper the design of a closed-loop system is presented. First, the operation principle of the thermal stepper is explained in more detail in section II. The section explains clarifies the need for a thermal control system based on experimental results with an open-loop solution. A thermal model of the mechanical system is used to derive the requirements and the specifications for the system, which can be found in section III. The main part, section IV, describes the design of the electronic control system.

Simulated results of the designed circuit are compared to measurement from the built-up open-loop system. Expected improvements of the final system, which are based on this analysis of the final system, are shown in section V. The paper ends with conclusions.

II. The Thermal Stepper Operation

1. Operating principle

The thermal stepper concept is based on thermal actuation, i.e. the displacement is generated by means of heating parts of the system. In this case the heated parts are the clamping elements, while the movement of interest is carried out by the clamped moving object Fig.2 shows a typical temperature profile of a thermal stepper system with four actuator elements (1,2,3, and 4) and the currently used open-loop control in time. Besides the temperature of the elements, the graph also shows the position of the moving object (d).

The stepping action of the actuator system is created by applying heat in a special order. In the first phase all elements are heated and the moving object moves based on the thermal expansion of the clamping elements. After the initial heating, the elements are cooled down one after the

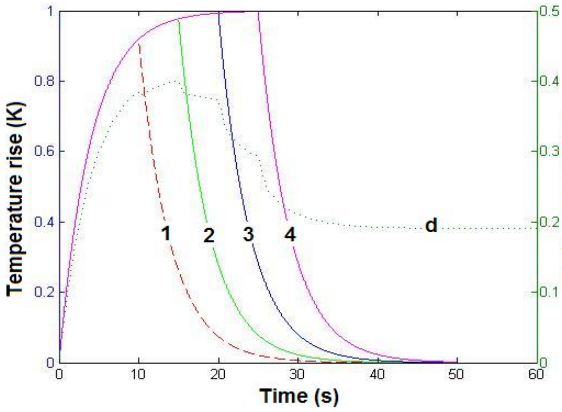

Fig 2. Simulated temperature and position profile of the four actuation element system with open loop control.

other. The cooling down procedure causes the element to contract and thus shorten. Since only one of the elements cools down at a time, the moving object is held in place by the other elements that are still heated up, while the contracting element will slip relative to the surface of the moving object. As can be seen in Fig.2, after completing a heating cycle, the moving object has made a permanent displacement relative to the base.

The open-loop heating and passive cooling in Fig.2 clearly shows an exponential behavior. This behavior causes a very slow approach of the elements towards their final temperature. Waiting for all the elements to reach their steady state value would make the system very slow; therefore a next step in the thermal cycle starts already when the temperature of some elements is still increasing or decreasing. This makes the system unpredictable and decreases the total step size.

A closed-loop temperature control system, can improve the performance of the thermal stepper. Since the temperature step T_{step} can be set to any value between initial and the maximum temperature, one can ensure that every element reaches a defined temperature. This implies that every element also has a defined length change. As shown in Fig.3, the control can be used to prevent an element from cooling down to its initial temperature. This enables the system to cool down relatively fast, due to the exponential behavior. As soon as the next element starts cooling down, the temperature of its predecessor can be fixed. This prevents two or more elements from contracting at the same time.

More advanced control strategies can be used to reduce stress in the elements after an adjustment cycle. Measurement data from the closed loop system can eventually be used to generate a feed forward signal that can be used in a more advanced open loop system.

2. Thermal model

The thermal stepper system contains several identical thermally-actuated elements, as shown in Fig.1. In our first analysis, a circuit electrically equivalent to the thermal model of one element was constructed, with the assumption that all the elements are identical in terms of their thermal characteristics. The equivalent circuit is shown in Fig.4. A heater is mounted in the center of the element. This allows the thermal model to be divided into two symmetrical parts.

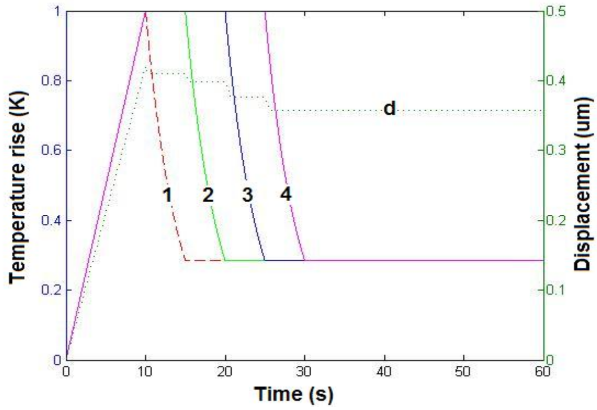

Fig 3. Simulated temperature and position profile of four actuation element system with closed-loop temperature control system.

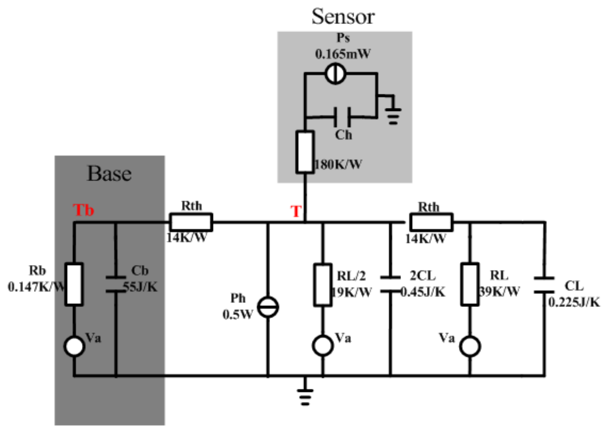

Fig. 4. Measured temperature profile of one element.

Each of these symmetrical parts is represented by a Π-network of two capacitors and one resistor. The sum of the capacitances represents the thermal capacitance of the element, which is calculated as follows [2]:

$$C_L = \rho c_p V \, , \tag{1}$$

where c_p [J kg^{-1} K$^{-1]}$ is the specific heat of the thermal element, ρ [kg/m$^{3]}$ is the density, and V [m^3] is the volume of the element. Resistances R_{th1} and R_{th2} represent the thermal resistances located between the center and two terminals of the element, which are determined by the physical dimension and the thermal conductivity of the element. The mathematical expression for the resistances is [2]:

$$R_{th} = (\mathrm{L/W}) \cdot (1/\kappa D), \tag{2}$$

where L, W and D indicate the length, width and thickness of the element, respectively. κ [K m^{-1}W^{-1}] is the thermal conductivity. R_L is defined as the thermal resistance between the thermal element and the ambient. Moreover, R_{sc} represents the thermal resistance between the element and sensor resulting from imperfect thermal contact, while C_s represents the thermal capacitance of the sensor.

The voltage source V_a in Fig.4 indicates the ambient temperature [3]. The current source P_h represents the heating power, which is determined by the heater resistance and the supply voltage. Another current source, P_s , indicates the power dissipation of the temperature sensor,

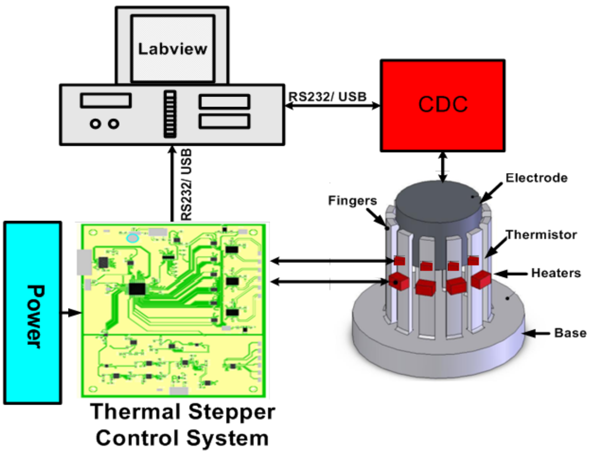

Fig. 5. Schematic of the test set up.

which is the source of the self-heating effect [4]. T indicates the temperature of the center of the element, and T_m represents the measured temperature.

As a result, the transfer function Gp(s) of the thermal process is found as:

$$G_p(s)=\frac{T(s)}{P_h(s)}=\frac{132s^2+73.4s+7.1}{59s^3+58.6s^2+14.4s+1} \quad (3)$$

The transfer function of the temperature measurement process Gm(s) can be expressed as:

$$G_m(s)=\frac{T_m(s)}{T(s)}=\frac{1}{1+sR_{sc}C_h} \quad (4)$$

III. Performance Requirements

In the design, the following working conditions are assumed:

(i) the ambient temperature is constant (varying within ± 0.5°C);

(ii) the heating of the actuator elements will not affect the environment temperature.

Based on the conditions, the performance requirements are defined as follow:

(i) the maximum temperature change of the elements is 30 °C, which corresponds to a step size of 5um;

(ii) the resolution of the temperature measurement is 0.01°C. This is to ensure small temperature ripples during the holding phase. As a result, the dynamic range can be calculated as 70dB (12-bit);

(iii) after the normal operation, the system has to be able to continuously measuring the ambient temperature change in order to compensate its effect on the electrode position. Therefore, the system has two operation modes. One is the self-alignment, while the other is the measurement for temperature drift;

(iv) the temperature measurement resolution of the 2nd operation mode is defined as 50µK. As a result, the dynamic range in this mode is 86dB (14-bit).

IV. Implementation of the Control Electronics

To demonstrate the performance of the control system, a demonstrator was created. The block diagram of the demonstrator, which is presented in Fig.5, contains four main functional blocks: the thermal stepper control system, capacitance-to-digital converter (CDC), Labview platform and an external power supply. The thermal stepper control system controls the heating and cooling of the heaters, based on the control algorithm. The position measurement is realized by the CDC board [6]. The external power supply included in the system provides power for the entire stepper system. The labview platform acts as an interface between the system and the operator for real-time monitoring and control.

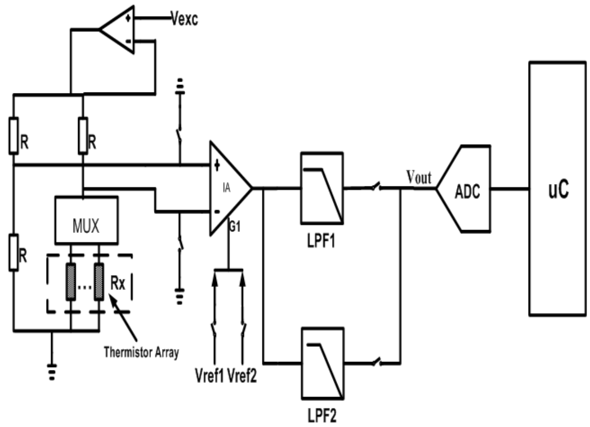

Fig. 6. Schematic of the test set up.

1. Temperature measurement

To measure the temperatures of the elements, thermistors are mounted on each of the elements. These thermistors are well-calibrated in advance to ensure good matching. The nominal resistance at 25°C is selected to be 22kΩ. This is with the consideration of both thermistor noise and the self-heating effect.

The block diagram of the readout electronics is shown in Fig.6. A typical Wheatstone bridge is constructed as the readout circuit of the thermistors. The thermistors are sharing the same bridge circuit by means of multiplexing. There are two reasons for such construction. Firstly, with this configuration, the thermistors are only powered when needed. It greatly reduces the self-heating effect. Secondly, because they are sharing the same readout circuit, the errors (offset, gain error, etc.) caused by the readout circuit are the same for all the measurement channels. As a result, the mismatches between the channels are minimized.

A low noise instrumentation amplifier is used to provide enough gain for the signal. Since there are two operation modes, each has different requirements on measurement resolution; two active low pass filters (LPF) are designed with different cut-off frequency. After the filtering, a 16-bit ADC digitizes the signal and sends the information to the microcontroller for processing. The microcontroller performs necessary calculation and controls the heating of the heaters.

2. Control strategy

Basically, there are three phases of operation: heating, holding and cooling. Firstly, the temperature should rise quickly in order to reduce the waiting time. Secondly, the temperature variation during the holding phase should be

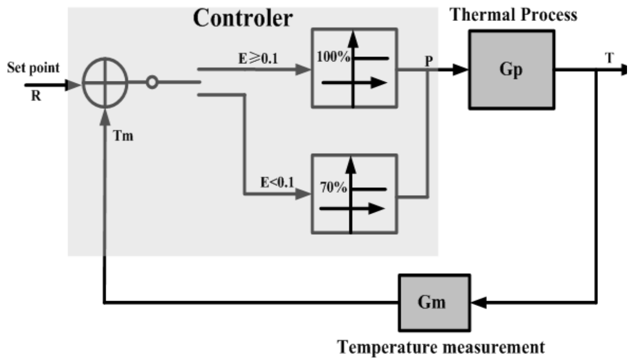

Fig. 7. Block diagram of the temperature control system.

minimal. Finally, and most importantly, the system stability must be guaranteed.

A modified ON/OFF control scheme was implemented in the first test set up because it is simple and cheap. The complete block diagram of the closed-loop control system is shown in Fig.7. The temperatures are periodically measured (Tm) and compared with a set point (R) to generate error signals (E). Then, based on the polarity and magnitude of this error signals, proper heating power (P) is applied to the thermal element. This resulted in controlling the temperature to be very close to the set point. Gp in Fig.7 indicates the transfer function of the thermal process, which is calculated in (3), and Gm is the transfer function of the temperature measurement, according to (4). The calculations and decision-making are performed in the microcontroller.

V. Simulations and Tests

Prior to building the designed control system, its performance was verified using a system-level simulation in MATLAB. The results of these simulations were compared to measurement results on the already built thermal stepper system with an open-loop control.

Fig.8 shows the results of the simulated closed-loop temperature control in combination with a model of the built system. The rise speed of the system temperature is high due to a relatively large heating power. Zooming to the constant temperature phase as in Fig.9 shows that the temperature varies within 0.025^{o}C around the set point, which is acceptably low.

VI. Conclusion

A new concept of high precision self-alignment system has been analyzed and possible control schemes have been discussed. An equivalent electrical model of the thermal behavior of the device has been made, which is very useful for accurate prediction of both the thermal and the related mechanical behavior of the device, and for optimization of the system performance.

The first measurement results, which used a simple open-loop control, successfully validated the new concept of thermal actuation. However, since the temperature is not well controlled in an open-loop system, optimizing the system for higher speed and greater accuracy is found to be difficult.

To achieve a faster and more accurate control, a low noise, high-speed closed-loop control system was designed.

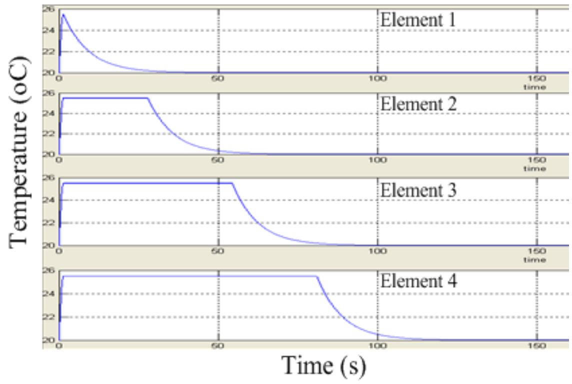

Fig.8. Complete operation cycle (four elements).

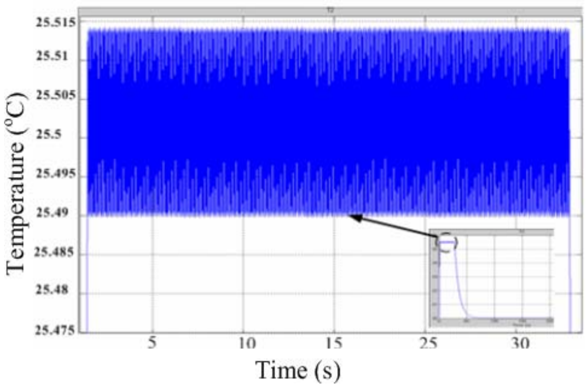

Fig. 9. Temperature variation during the holding phase.

The closed-loop control process was simulated in MATLAB, and the results indicate better performance compared to the open-loop system in terms of speed and accuracy.

At this moment, the circuit board of the closed-loop control system is under development. More tests and optimizations with the complete closed-loop control system will be made in the near future.

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