Cryogenic Performance of Piezo-Electric Actuators for Opto-Mechanical Applications

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ABSTRACT

Space telescope designs driven by science goals such as the infrared observation of high-redshift galaxies and the infrared observation of objects that would otherwise be obscured by dust in the visible push the operating temperatures of the optics to cryogenic temperatures. Typical temperatures, 30 to 100 K are a challenging regime for actuators, but little information is available on the low-temperature performance of Piezo-electric actuator products currently on the market. Work is underway to measure actuator stroke and CTE, at low temperatures for typical PZTs, such as those available "off-the-shelf" from P.I. and Thorlabs.

Keywords: cryogenic actuators, cryogenic structures, opto-mechanics, piezo-electric materials, PZT actuators

1. INTRODUCTION

The JPL cryo-dilatometer facility[1,2,3] has been used to measure the low temperature thermal strain of popular low-CTE materials such as Corning ULE[1], silicon carbide and Invar[4], and certain actuator materials[5]. For actuator materials it is also desirable to characterize their mechanical response to electrical inputs as a function of temperature. Typical piezo-electric materials lose most of their electro-mechanical gain as they are cooled from room-temperature to cryogenic temperatures[6], although the magnitude of the gain loss is highly material dependent.

The JPL facility has been adapted to simultaneously measure both the thermal strain **and** the electro-mechanical gain of actuators as a function of temperature from 324 K down to ~30 K. In this paper we present results from a preliminary run with a commercial off-the-shelf PZT device: the P.I. P-802.10. This particular device is no longer produced by Physik Instrumente, but it is nevertheless typical of general-purpose PZT actuators. Work is underway to test currently available PZT actuators: the Thorlabs AE0203D08F and the P.I. P-885.30. If time and funding permit, we will extend the measurements to include the Piezosystem Jena P-214-40. The reader is invited to contact the authors for recent results, or to search the literature for future publication of our data.

2. EXPERIMENT

Normally the JPL cryo-dilatometer uses samples in the configuration shown in figure 1. The downward laser beams are part of a Michelson interferometer that accurately measure changes in the vertical position of the sample's top surfaces. In the mode of figure 1, if a temperature change causes the length (the vertical dimension) of the sample pillar to increase, then the optical path of the central beam relative to the three outer beams is reduced. However this sample configuration requires that the top of the sample pillar be polished to reflect the central laser beam, and that the top surface of the pillar be parallel to the base to better than 20 micro-radians. Since polishing actuators is difficult, and because actuators usually bend slightly when energized, it is not practical to simply substitute an actuator for the sample pillar.

To resolve these issues, the configuration in figure 2 was introduced. It effectively measures the average behavior of three identical actuators that are supporting a mirror with a central hole (the "donut"). In this mode, if a temperature change causes the height of the sample actuators to increase, then the optical path of the **outer** beams, relative to the central beam is reduced. The base and mirror material is single-crystal silicon, chosen because of its stability, high thermal conductivity and well-known CTE. Figure 2 also shows how the donut's CTE can be compensated by placing a

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small mirror on the base, under the central beam. Since it is also made of silicon, and has a thickness equal to the donut's, its presence cancels the thermal expansion of the donut. If the mirror is not present, the CTE of the donut can still be accounted for since the CTE of silicon is known to high accuracy. In the data presented here, the compensation mirror was used.

This sample configuration requires that the top surface of the donut be parallel to the base to better than 20 micro-radians, but this is easily achieved by (a) lightly sanding the actuator ends which are usually made of an inert material and (b) by adding small offset voltages to one or two of the actuators. Figure 3 shows sample actuators in the apparatus prior to testing.

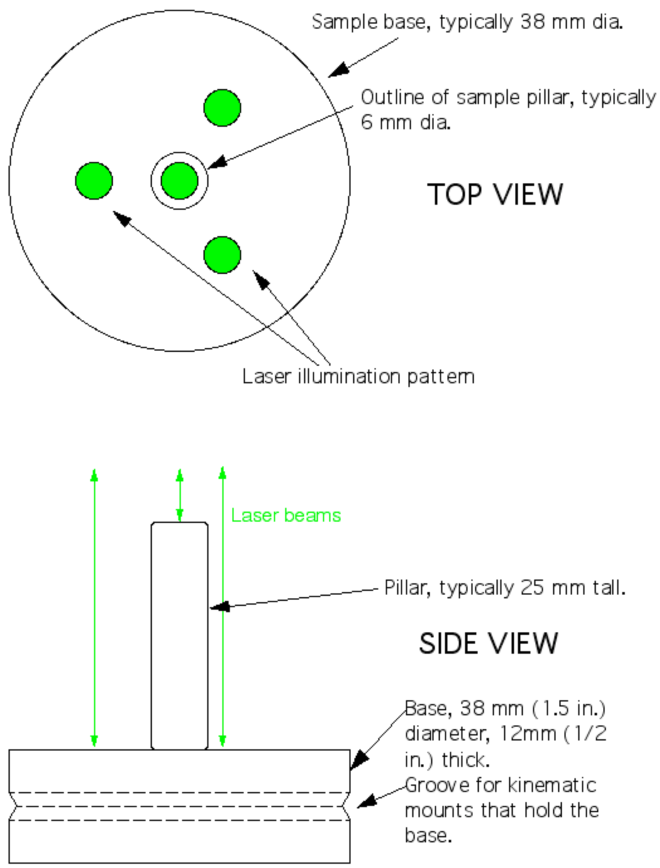
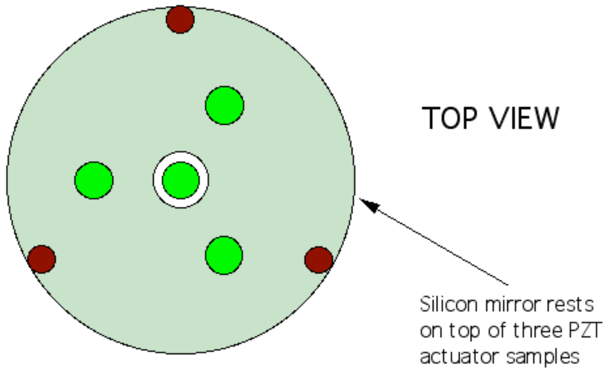


Fig 1. Normal configuration of samples for thermal strain and CTE measurement. Because this setup requires that the top of the sample be polished to mirror finish, it does not work well for actuators.

The testing process consists of:

1. Measuring the room temperature lengths of the actuators and installing them with temperature sensors as in figures 2 and 3.
2. Aligning the base to be orthogonal to the central laser beam to obtain interference fringes.
3. Applying offset voltages to the sample actuators to make the donut parallel to the base to obtain fringes on the outer laser beams.
4. Applying a "square-wave" voltage pattern to the three actuators such that they will all lengthen/shorten together. A typical waveform is 50 volts peak-to-peak at 0.28 milli-Hertz. This gives a 30 minute on, 30 minute off pattern.

The applied voltage is supplied by a Thorlabs MDT693A piezo controller. This device has a low output impedance, so the voltage applied to the PZT actuators is well defined.



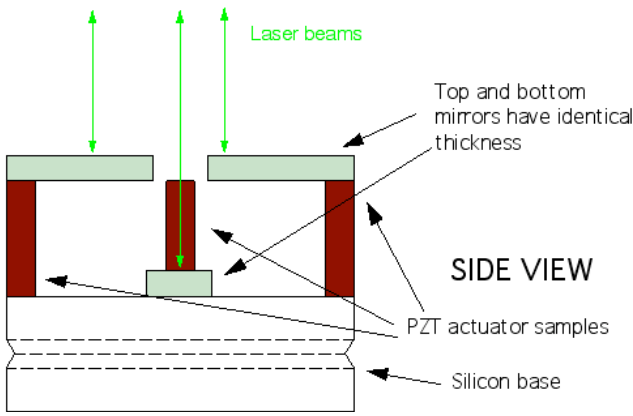


Fig 2. Modified configuration used for actuator testing. Three identical actuators support a mirror with a central hole (the "donut"). This mode requires that the three actuators maintain lengths equal to a few microns, a requirement that is easily achieved by adding small offsets to the voltages on the actuators. The central laser beam reflects either from the base or, as shown here, from a small mirror of thickness and composition identical to the donut, to compensate for the donut's CTE.

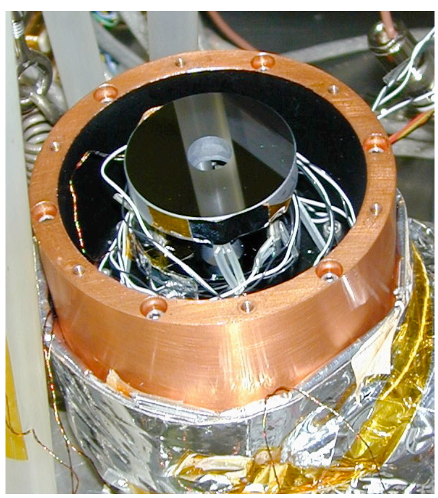


Fig. 3. View of the donut-shaped mirror supported by three piezo-electric actuators, ready for cryo-testing. The actuators and mirror are instrumented with temperature sensors. The copper container has a cover (with holes to allow laser beams to enter) so that the entire sample assembly is in a homogeneous cryogenic environment.

3. RESULTS AND DISCUSSION

We will be testing the Thorlabs AE0203D08F and the PI P-885.30 PZT actuators, however these data are not yet available. Instead, we present early results from the P.I. P-802.10. Its characteristics[7], from the manufacturer are listed in table 1.

Table 1. Physical and electrical parameters of PZT actuator tested.

Manufacturer, Model	Physik Instrumente, P-802.10
Room temperature travel, 1-100 V	15 microns
Length (in direction of travel)	18 mm (17.938 mm room temperature length measured.)
Cross-section	6 x 6 mm
Room temperature stiffness	200 N/micron
Room temperature capacitance	1.8 micro-farads
Nominal temperature range	-20 to +80 C (293 to 353 K)

The actuators were installed as shown in figure 3 and the voltages applied. The square-wave voltages are listed in table 2. The off and on states were each 30 minutes long so the square wave has a 60 minute period.

Table 2. Voltages applied to actuators under test.

Piezo #	Off-state voltage	On-state voltage
1	0.23	59.2
2	57.5	116.5
3	55.2	114.3

Strain and CTE

Figure 4 shows the raw data from the dilatometer, while figures 5, 6, and 7 show the thermal strain in the "average", off and on states. All of the strain curves have been adjusted so that the fit passes through zero strain at 293.15 K, regardless of the electro-mechanical state of the actuators when 293.15 K was reached. The strain and CTE curves may be reproduced by using the polynomials in table 3.

Already, this preliminary data reveals a few interesting things:

1. These actuators have a negative CTE. Hence they **become shorter** when heated, **longer** when made cold. (At least this is true in the actuation direction.)
2. The electromechanical gain, or stroke, is fairly stable from 325 K down to 200 K, but it falls to 38% of its room-temperature value as the temperature falls to 100 K.
3. The on-state CTE approaches zero as the temperature approaches 100K.

The measurements under way will go down to about 30K, allowing further exploration of PZT behaviour.

Errors

The temperature uncertainty in these measurements is about +/- 0.25 K from room temperature down to 180 K. From 180 K down to 100 K it linearly increases to +/- 1.8 K.

The length change uncertainty is +/- 0.67 nm (interferometer error) or, for a sample length of 18 mm, a strain uncertainty of +/- 3.7×10^{-9}.

The error from the uncertainty in the room-temperature length of the actuators scales with strain. So, given that the room-temperature length of the actuators is known to +/- 2 microns, the room-temperature length error contributes a strain error of 0 at room temperature, linearly increasing to 4.4×10^{-8} at a strain of 4×10^{-4}.

The largest source of error is one that cannot be easily quantified: it is the hysteresis of the PZT material, which can easily add on the order of 5% uncertainty to the strain. Accompanying the hysteresis, there is “creep” which causes the actuators to not respond immediately to the edges of the square-wave signal. Instead, after an initially rapid motion, the actuator slowly “creeps” towards a final position on a time scale of many hours. That can be observed in figure 4 as a slight rounding of the leading edges of the square-wave motion.

Finally, the data is not from a single PZT actuator, but is actually the combined response of the three devices supporting the donut. This would not be a problem if it weren’t for the DC biases applied to two of the three actuators (table 2) as required to bring the donut into alignment. This issue will be addressed in the new round of actuator measurements.

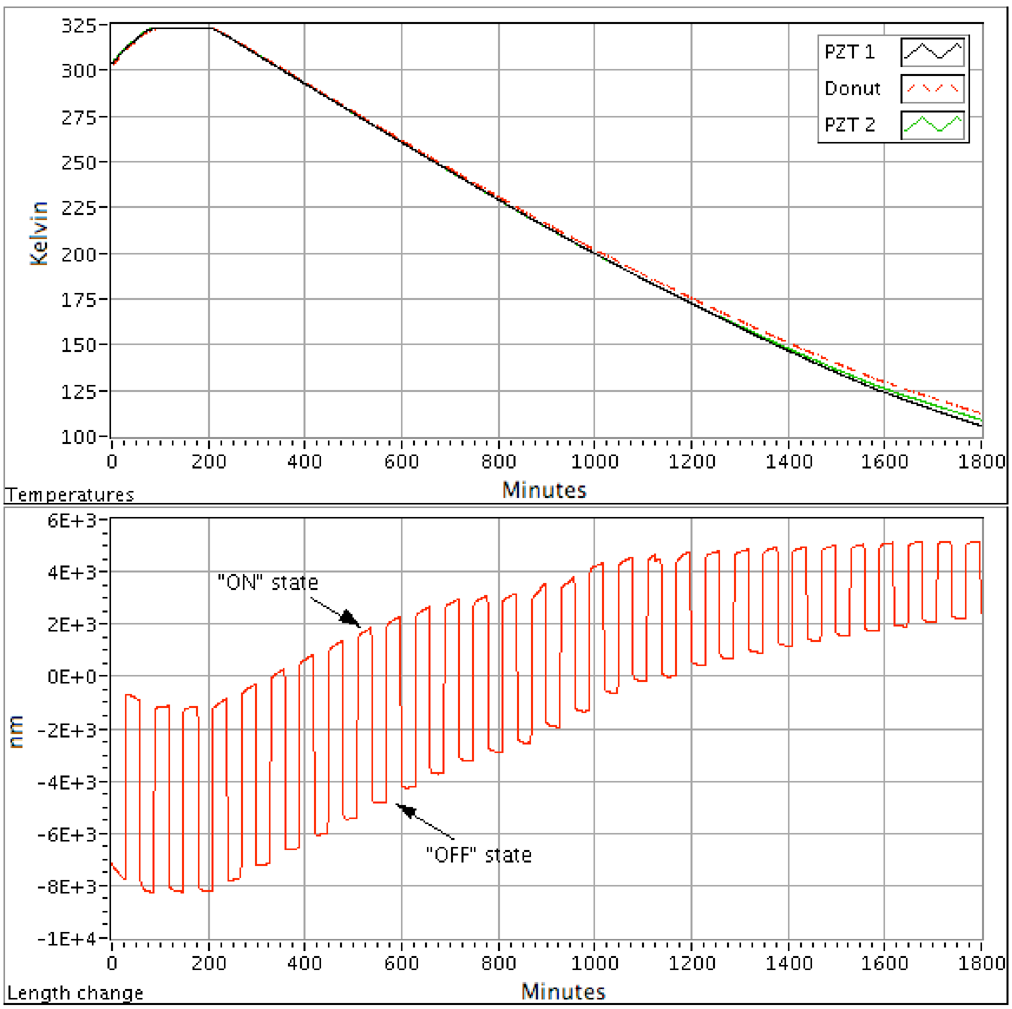


Figure 4. Raw data from PZT actuator test. Upper plot shows sample and “donut” mirror temperatures. Lower plot shows relative displacement of donut caused by actuator extension and CTE. The square-wave like displacement is due to the square-wave voltage applied to the actuators. The increasing trend in the displacement is due to the decreasing temperature causing the actuators to lengthen, indicating that these actuators have a negative CTE.

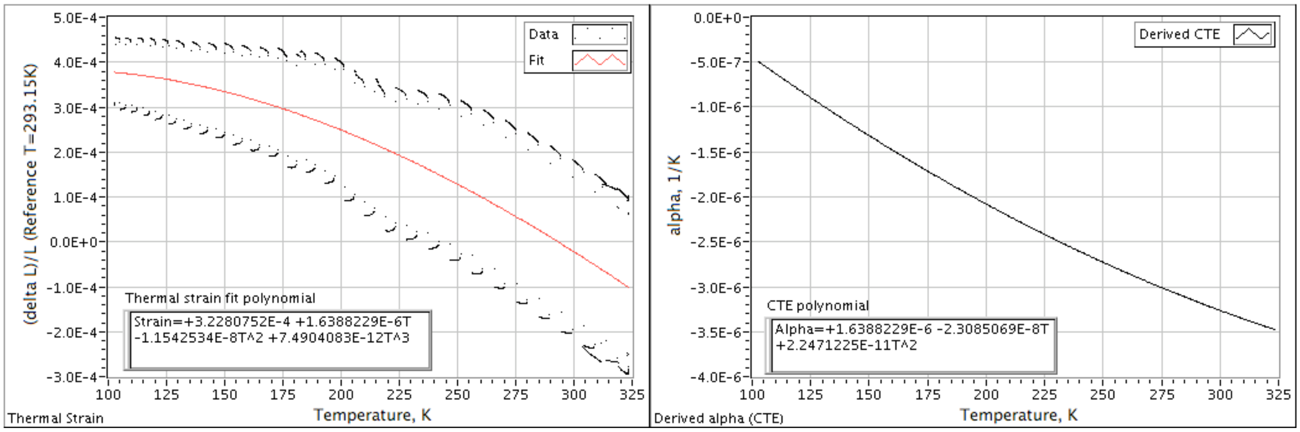


Fig 5. On and off-states “averaged” strain (referred to 293.15 K) and CTE. The fitter that produced the polynomial (red curve) used both the on-state data (upper clusters of data points) and the off-state data (lower clusters). Hence the fit is a compromise between the two states, very nearly the average.

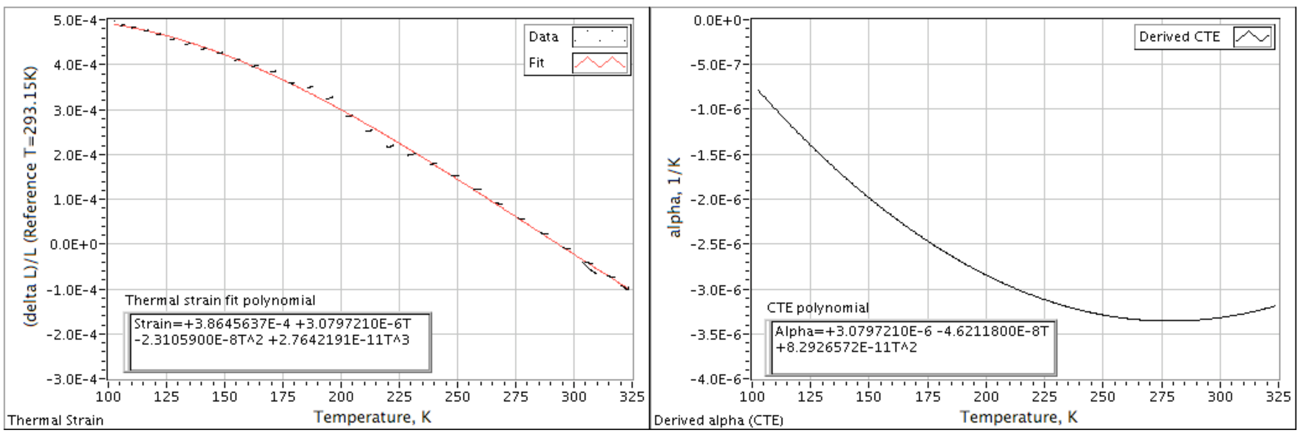


Fig 6. Off state strain (referred to 293.15 K) and CTE.

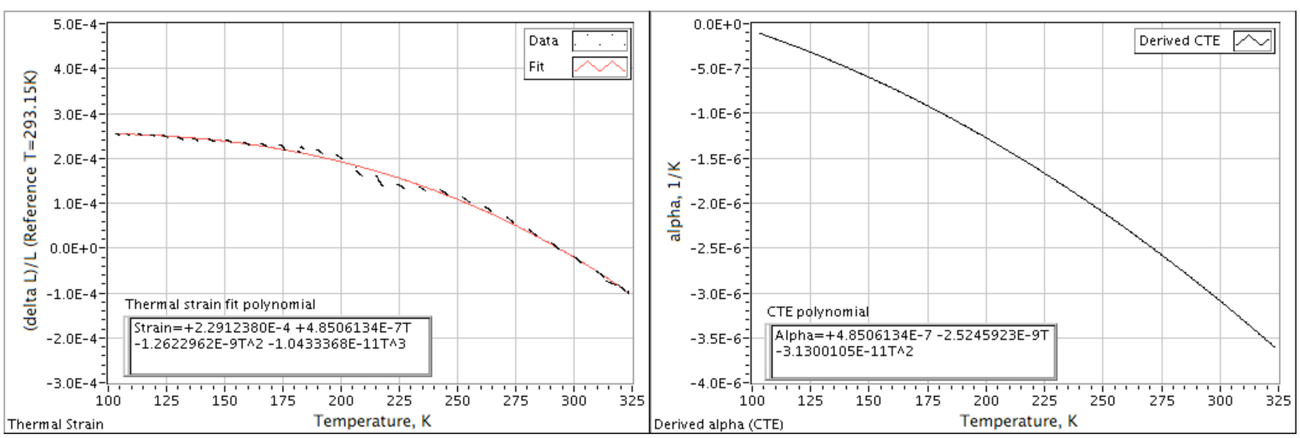


Fig 7. On state strain (referred to 293.15 K) and CTE.

Table 3. Measured strains and CTEs, converted to polynomial fits. The large number of digits are needed for accurate polynomial evaluations and do not imply accuracy beyond what is claimed elsewhere in this paper.

Piezo state	Strain polynomial	CTE polynomial
ON, OFF average	+3.1883409E-4 +1.6964384E-6T -1.1802515E-8T^2 +7.8645434E-12T^3	+1.6964384E-6 -2.3605030E-8T +2.3593630E-11T^2
OFF state	+3.8645637E-4 +3.0797210E-6T -2.3105900E-8T^2 +2.7642191E-11T^3	+3.0797210E-6 -4.6211800E-8T +8.2926572E-11T^2
ON state	+2.2912380E-4 +4.8506134E-7T -1.2622962E-9T^2 -1.0433368E-11T^3	+4.8506134E-7 -2.5245923E-9T -3.1300105E-11T^2

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REFERENCES

1. M. J. Dudik, P. G. Halverson, M. Levine, M. Marcin, R. D. Peters, S. Shaklan, "Precision cryogenic dilatometer for James Webb space telescope materials testing," presented at the Fifteenth Symposium on Thermophysical Properties, June 22-27, 2003, Boulder, Colorado, U.S.A.
2. M. J. Dudik, P. G. Halverson, M. B. Levine, M. Marcin, R. D. Peters, S. Shaklan, "Development of a precision cryogenic dilatometer for James Webb Space Telescope materials testing," Proceedings of the SPIE, Volume 5179, pp. 155-164 (2003).
3. P. B. Karlmann, M. J. Dudik, P. G. Halverson, M. B. Levine, M. Marcin, R. D. Peters, S. B. Shaklan, D. Van Buren, "Continued development of a precision cryogenic dilatometer for the James Webb Space Telescope," Proceedings of the SPIE, Volume 5528, pp. 63-71 (2004).
4. P. G. Halverson, T. J. Parker, P. Karlmann, K. J. Klein, R. D. Peters, M. Levine, "The JPL cryogenic dilatometer: measuring the thermal expansion coefficient of aerospace materials," proceedings of the ITCC29/ITES17, Birmingham, Alabama, 24-27 June, 2007
5. P. B. Karlmann, K. J. Klein, P. G. Halverson, R. D. Peters, M. B. Levine, D. Van Buren, M. J. Dudik, " Linear thermal expansion measurements of lead magnesium niobate (PMN) electroceramic material for the Terrestrial Planet Finder Coronagraph," Proceedings of the SPIE, Volume 5868, pp. 192-201 (2005).
6. P. Pertsch, H. Marth, P. Anger, and A. Feltz, "Low-temperature properties of piezoelectric actuators," ACTUATOR 2000, 7th International Conference on New Actuators, 19-21 June 2000, Bremen, Germany .
7. http://www.physikinstrumente.com/pztactuators/1_6t.html