Performance analysis and characterisation of micro-nanopositioning systems

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Separation and quantification of error components in micro-nanopositioning systems are presented with theoretical analysis and experimental characterisation, which are illustrated with a single-axis nanopositioning stage. The concepts of intrinsic and extrinsic repeatabilities are proposed.

Introduction: Nowadays, micro-nanopositioning systems are applied to widespread applications of micro-nanotechnology and engineering [1–3]. To fulfil the tasks at the micro-nanoscale level, micro-nanopositioning systems are designed with high precision down to the nanometre range. However, the positioning performance is affected by a variety of sources. As far as we know, there is no literature dealing with separation and quantification of error components theoretically and experimentally. There is no clear formulation analysis to distinguish different error components induced by different sources in micro-nanopositioning systems. As a typical case, a theoretical analysis and experimental characterisation of a single-axis nanopositioning stage (P-625.1CD, Physik Instrumente) [4] are presented in this Letter.

Theoretical analysis: Without loss of generality, the following calculation and analysis will be based on a one degree of freedom (1-DoF) case which is easy to expand to multi-DoF. The 1-DoF nanopositioning stage, given the target input x_T, is measured by an external sensor, and its real position is x_m defined by

$$x_m = G(x_T) + L(t) = P(x_T) + x_T + g(x_T) + L(t) \tag{1}$$

where $G(x_T)$ is the latent geometric model depicting the real displacement; $L(t)$ is the drift induced by environment (we will consider thermal effect) acting on the nanopositioning stage; $P(x_T)$ is the error component inherent in the nanopositioning stage; $g(x_T)$ is the position-dependent error corresponding to joint input x_T. $g(x_T)$ is named as intrinsic error which cannot be compensated for. This error results from the control precision of actuator layer which is affected by controller capability and resolution of internal sensor. Fig. 1 shows the geometric representation of every component of input–output of the 1-DoF nanopositioning stage. $P(x_T)$ can be minimised by robot calibration. $g(x_T)$ can be minimised by design, fabrication and setting.

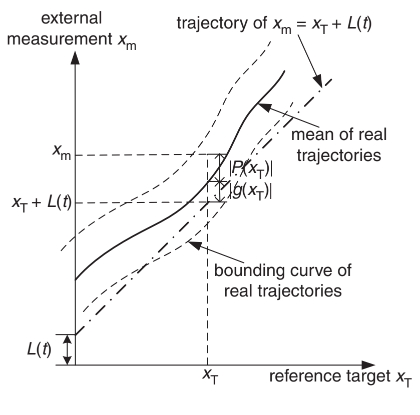

Fig. 1 *Geometric representation of every component of input–output of 1-DoF nanopositioning stage*

Theorem: The accuracy of the nanopositioning stage is degraded by geometric error, intrinsic and external errors; the repeatability is a combination of intrinsic part and extrinsic part represented by an external drift.

Proof: For a given pose, the accuracy expresses the deviation between the command target x_T and the mean of a set of measured poses $\overline{x_m} = (1/n)\sum_{i=1}^{n} x_{mi}$ when reaching the target n times. The one-dimensional accuracy (AP) can be calculated by virtue of the calculation methods of ISO 9283 [5]:

$$\begin{aligned} \mathrm{AP} &= |\overline{x_m} - x_T| = \left|\frac{1}{n}\sum_{i=1}^{n} x_{mi} - x_T\right| \\ &= \left|\frac{1}{n}\sum_{i=1}^{n}[G_i(x_T) + L_i(t)] - x_T\right| \\ &= \left|\frac{1}{n}\sum_{i=1}^{n}[P_i(x_T) + g(x_T) + x_T + L_i(t)] - x_T\right| \\ &= \left|g(x_T) + \frac{1}{n}\sum_{i=1}^{n}P_i(x_T) + \frac{1}{n}\sum_{i=1}^{n}L_i(t)\right| \end{aligned} \tag{2}$$

The repeatability (RP) expresses the closeness of agreement between n measured poses as

$$\begin{aligned} \mathrm{RP} &= \frac{1}{n}\sum_{i=1}^{n}|x_{mi} - \overline{x_m}| + 3\sigma \\ &= \frac{1}{n}\sum_{i=1}^{n}\left|G_i(x_T) + L_i(t) - \frac{1}{n}\sum_{j=1}^{n}[G_j(x_T) + L_j(t)]\right| + 3\sigma \\ &= \frac{1}{n}\sum_{i=1}^{n}\left|P_i(x_T) - \frac{1}{n}\sum_{j=1}^{n}P_j(x_T) + L_i(t) - \frac{1}{n}\sum_{j=1}^{n}L_j(t)\right| + 3\sigma \end{aligned} \tag{3}$$

where σ is the standard deviation. □

Assuming that there is no external disturbance, the accuracy of the nanopositioning stage is determined by geometric and intrinsic errors:

$$\mathrm{AP_I} = \left|g(x_T) + \frac{1}{n}\sum_{i=1}^{n}P_i(x_T)\right| \tag{4}$$

The repeatability is determined absolutely by intrinsic errors

$$\mathrm{RP_I} = \frac{1}{n}\sum_{i=1}^{n}\left|P_i(x_T) - \frac{1}{n}\sum_{j=1}^{n}P_j(x_T)\right| + 3\sigma_I \tag{5}$$

$\mathrm{RP_I}$ comes from the intrinsic part ($P(x_T)$) of the stage, and is called intrinsic repeatability.

With error compensation, $q = x_T + g'(x_T) + L'(t)$ replaces x_T as control input:

$$\begin{aligned} x_m &= G(q) + L(t) = g(q) + P(q) + q + L(t) \\ &= g(x_T + g'(x_T) + L'(t)) + P(x_T + g'(x_T) \\ &\quad + L'(t)) + x_T + g'(x_T) + L'(t) + L(t) \end{aligned}$$

where $g'(x_T)$ and $L'(t)$ are inputs that compensate for geometric and thermal errors, respectively.

In reality, $g'(x_T)$ and $L'(t)$ are small ($g'(x_T) < 0.4$ µm and normally $g'(x_T) \le 5$ µm), so $g(x_T + g'(x_T) + L'(t)) \approx g(x_T)$ and $P(x_T + g'(x_T) + L'(t)) \approx P(x_T)$. Moreover, since $g(x_T)$ is relatively simple and steady, the hypothesis of perfect compensation of geometric error is strong, namely $g'(x_T) = -g(x_T)$. Then

$$\begin{aligned} x_m &= g(x_T) + P(x_T) + x_T + g'(x_T) + L'(t) + L(t) \\ &= P(x_T) + x_T + T(t) \end{aligned}$$

If the compensation of the thermal model is perfect, $T(t) = 0$, then $x_m = x_T + P(x_T)$. However, complete compensation of thermal drift is difficult if not impossible.

Therefore, when subjected to external disturbances, the accuracy of the micro-positioning stage using calibration is degraded by intrinsic errors and residual errors of imperfect compensation based on the assumption of complete compensation of geometric error:

$$\mathrm{AP_S} = \left|\frac{1}{n}\sum_{i=1}^{n}P_i(x_T) + \frac{1}{n}\sum_{i=1}^{n}T_i(t)\right| \tag{6}$$

The repeatability is a combination of intrinsic part and extrinsic part represented by residual drift:

$$\mathrm{RP_S} = \frac{1}{n}\sum_{i=1}^{n}\left|P_i(x_T) - \frac{1}{n}\sum_{j=1}^{n}P_i(x_T) + T_i(t) - \frac{1}{n}\sum_{j=1}^{n}T_i(t)\right| + 3\sigma_C \tag{7}$$

In summary, repeatability can be divided into two types: intrinsic and extrinsic repeatabilities. Intrinsic repeatability is the characteristic of the stage itself and is only relevant to the geometric nature of the microrobot and controller capability. Extrinsic repeatability is the summation of intrinsic repeatability and the portion affected by the external environment. Intrinsic repeatability is relatively stable (in our case, about 40 nm). Extrinsic repeatability changes with external factors (temperature in this case). In general, the deviation of temperature is wider and the extrinsic repeatability is larger. Under the same condition of temperature changing, the repeatability with thermal compensation is greater than that with no compensation. The final accuracy and repeatability are determined by the maximum values of the test with M testing poses:

$$\mathrm{AP} = \max(\mathrm{AP}_i), \quad \mathrm{RP} = \max(\mathrm{RP}_i), \quad i = 1,\ 2,\ \ldots,\ M$$

Geometric errors: Geometric errors at the microscale are the main nonlinearities inherent in the nanopositioning stage [4]. To quantify the geometric errors, the nanopositioning stage is controlled to reach some positions and the actual positions are measured by an external sensor (in this case, an interferometer). Fig. 2 shows the position-dependent errors of the nanopositioning stage measured by the external sensor and the one provided by the supplier of the nanopositioning stage. In this case, the curve of the errors is a cubic function (third-order) with two critical points. The errors are major (up to 400 nm) in nanopositioning, even though the stage has benn closed-loop controlled at the actuator layer. The peak-valley value measured by the supplier is also about 400 nm. The error curve has been moved in parallel which is due to long-term use. This error is repeatable and can be compensated for down to a few tens of nanometres.

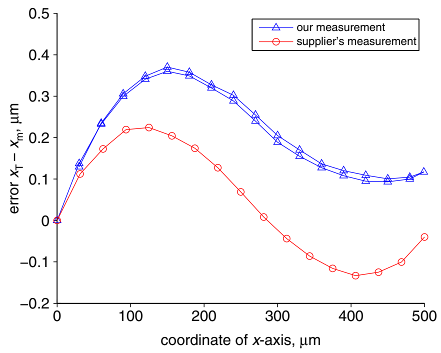

Fig. 2 *Geometric errors of nanopositioning stage*
x_T is target and x_m is measured position along x

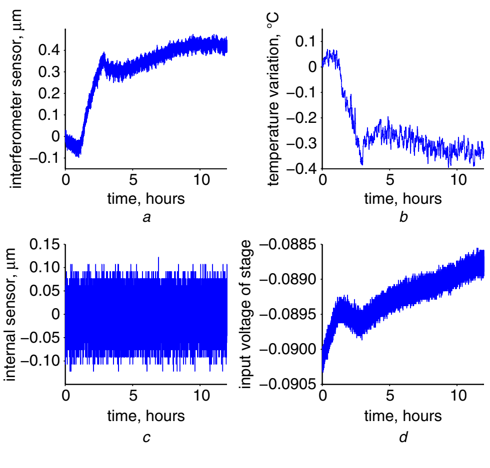

Fig. 3 *Results of position measurement experiment*
a Measurement of stage position by interferometer
b Measurement of ambient temperature close to stage
c Measurement of internal sensor of stage
d Input voltage of stage

Thermal drift: Except for geometric errors, the system is also highly susceptible to thermal disturbances [4]. For instance, we use proportional–integral–differential (PID) control to keep a nanopositioning stage at its zero position (reference position) with an internal capacitance sensor. The interferometer measures the real position of the stage. In Figs. 3*a* and *b*, there is drift in position up to 400 nm when temperature decreases by 0.35°C (measured by a *K*-type thermocouple). However, the internal sensor gives us constant information (with 100 nm measuring noises in Fig. 3*c*). Fig. 3*d* shows that the control input (also the output of the PID controller) of the stage changes somewhat during this time, which means the internal sensor detects a part of the drift and the controller compensates for it, but not sufficiently. From an internal sensor point of view, there is no motion; from an external sensor point of view, there is a motion. The internal sensor misses the part detected by the interferometer. This is because the internal sensor makes indirect measurement which is different from the direct measurement by the interferometer. The source is likely to be that there is a deformation on the robot structure under temperature change. However, the model used to estimate real motion based on the internal sensor has constant parameters.

Moreover, we perform an experiment to characterise the relation between temperature and drift, where the interferometer is used to measure the position of the switched-off nanopositioning stage. The interferometer is defined as a global frame in two days of measurement. Even though there is no inputting of moving commands, the interferometer detects the drift of the stage. Fig. 4 shows that there is drift increasing with the temperature decreasing in an opposite way, which is roughly a linear relation between temperature variation and position drift.

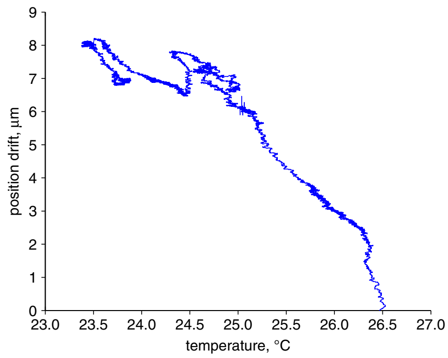

Fig. 4 *Relationship between temperature and thermal drift of nanopositioning stage*

Conclusion: To fill the absence of research, this Letter presents separation and quantification of error components in micro-nanopositioning systems. A theoretical analysis is presented for the single-axis nanopositioning stage, which is a typical example of micro-nanopositioning systems. The concepts of intrinsic and extrinsic repeatabilities are proposed. The experimental results give the characterisation of the two main errors, namely geometric error and thermal drift.

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One or more of the Figures in this Letter are available in colour online.

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References

1 Chaillet, N., and Régnier, S.: 'Microrobotics for Micromanipulation' (Wiley-ISTE, 2010)
2 Cheng, Y.X., Zhang, W.P., Guan, R., Zhang, G., Xu, Z.X., and Chen, W. Y.: 'MEMS-based piezoelectric BAW resonator based on out-of-plane degenerate mode for micro angular detector', *Electron. Lett.*, 2013, **49**, (6), pp. 406–407
3 Dai, X.H., Ding, G., and Zhao, X.L.: 'Batch fabricated long throw bi-stable electromagnetic micro-actuator', *Electron. Lett.*, 2010, **46**, (9), pp. 638–639
4 Tan, N., Clévy, C., and Chaillet, N.: 'Calibration of single-axis nanopositioning cell subjected to thermal disturbance'. Proc. IEEE Int. Conf. Robotics and Automation (ICRA), Karlsrune, Germay, 6–10 May 2013, pp. 3645–3650
5 'Manipulating industrial robots – performance criteria and related test methods', ISO 9283, 1998