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COMPUTER SCIENCE MEETS AUTOMATION

VOLUME I

Session 1 - Systems Engineering and Intelligent Systems
Session 2 - Advances in Control Theory and Control Engineering
Session 3 - Optimisation and Management of Complex Systems and Networked Systems
Session 4 - Intelligent Vehicles and Mobile Systems
Session 5 - Robotics and Motion Systems

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Preface

Dear Participants,

Confronted with the ever-increasing complexity of technical processes and the growing demands on their efficiency, security and flexibility, the scientific world needs to establish new methods of engineering design and new methods of systems operation. The factors likely to affect the design of the smart systems of the future will doubtless include the following:

- As computational costs decrease, it will be possible to apply more complex algorithms, even in real time. These algorithms will take into account system nonlinearities or provide online optimisation of the system's performance.
- New fields of application will be addressed. Interest is now being expressed, beyond that in "classical" technical systems and processes, in environmental systems or medical and bioengineering applications.
- The boundaries between software and hardware design are being eroded. New design methods will include co-design of software and hardware and even of sensor and actuator components.
- Automation will not only replace human operators but will assist, support and supervise humans so that their work is safe and even more effective.
- Networked systems or swarms will be crucial, requiring improvement of the communication within them and study of how their behaviour can be made globally consistent.
- The issues of security and safety, not only during the operation of systems but also in the course of their design, will continue to increase in importance.

The title "Computer Science meets Automation", borne by the 52nd International Scientific Colloquium (IWK) at the Technische Universität Ilmenau, Germany, expresses the desire of scientists and engineers to rise to these challenges, cooperating closely on innovative methods in the two disciplines of computer science and automation.

The IWK has a long tradition going back as far as 1953. In the years before 1989, a major function of the colloquium was to bring together scientists from both sides of the Iron Curtain. Naturally, bonds were also deepened between the countries from the East. Today, the objective of the colloquium is still to bring researchers together. They come from the eastern and western member states of the European Union, and, indeed, from all over the world. All who wish to share their ideas on the points where "Computer Science meets Automation" are addressed by this colloquium at the Technische Universität Ilmenau.

All the University's Faculties have joined forces to ensure that nothing is left out. Control engineering, information science, cybernetics, communication technology and systems engineering – for all of these and their applications (ranging from biological systems to heavy engineering), the issues are being covered.

Together with all the organizers I should like to thank you for your contributions to the conference, ensuring, as they do, a most interesting colloquium programme of an interdisciplinary nature.
I am looking forward to an inspiring colloquium. It promises to be a fine platform for you to present your research, to address new concepts and to meet colleagues in Ilmenau.

Professor Peter Scharff
Rector, TU Ilmenau

Professor Christoph Ament
Head of Organisation

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2 Advances in Control Theory and Control Engineering

52nd Internationales Wissenschaftliches Kolloquium
Technische Universität Ilmenau
10 – 13 September 2007

J. Zimmermann / O. Sawodny

Modelling and Control of a X-Y-Fine-Positioning Table

1. ABSTRACT

This contribution is about the modelling, simulation and control of an x-y-high precision positioning table and summarises results from a research work supported by the collaborative research centre SFB 622 'Nanopositionier- und Nanomessmaschinen' of the Technische Universität Ilmenau. The setup provides an operating range of 200x200mm² and is build up in a double-H configuration.

For modelling of the two dimensional system a Langrangian approach, with three mass approximation and couplings between the axes, was utilised. Additionally the friction of the four guides was implemented using the elasto-plastic friction model [3,4]. Since the normal force of the guides of the x-axis depends on the position of the y-axis, the friction model also must provide these properties. Therefore the model was adapted according to the results of an unequally stressed guide [8].

The control task is high precision path-tracking and fine positioning of multiple axes for coordinated movements. Therefore a PI state feedback controller with feedforward path is compared with a robust double-integrator control scheme [7] using the developed simulation model.

2. X-Y-POSITIONING TABLE

The setup which motivates this work was constructed by Steffen Hesse, member of the collaborative research centre SFB 622. It provides an operating range of 200x200mm² and is build up in a double-H configuration, which means there are two guides and drives for each axis. Both axes are coupled by a torsional stiffness of the two guides of each axis and a flexural stiffness between the two axes, which is modelled by spring-damper-elements.

Furthermore the accelerated mass of both guides of the x-axis depends on the position of the y-axis. This also involves the normal force and thereby the friction force of the guides, which is handled in section 3. Positioning of the tool-center-point with parallel feed of the axes is the main control task, which means the y-axis can be simplified to only one motor and guide for the Langrangian approach. Thus a three-mass model is developed, compare Fig. 1.

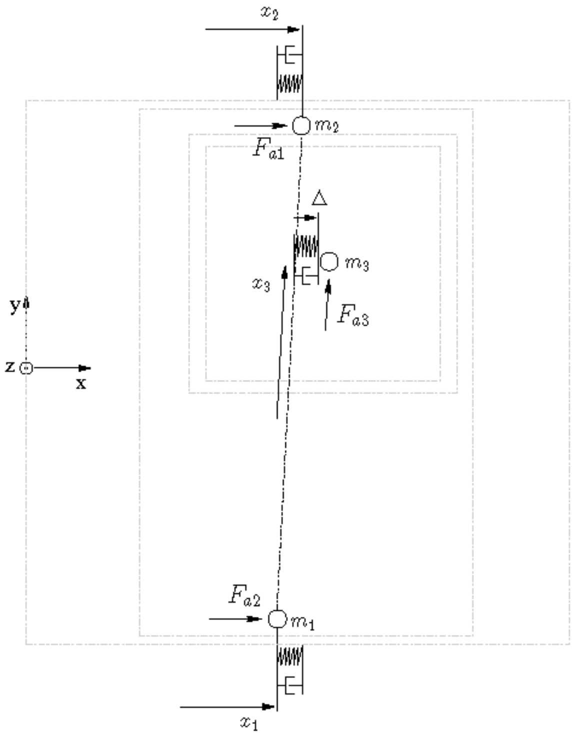

Fig. 1. x-y-table visualisation

Centres of gravity of the axes and locations of the corresponding motors and guides are arranged such that torsional movements are reduced, so there is no need to model the z-coordinates of the system. Additionally the following assumptions have been made:

- all masses are combined to three time dependent point masses
- friction is handled as an external force
- there is no torque causing torsional stress
- the is no bowing under load of the carrier

The resulting differential equations are derived from Mathematica® and implemented in MATLAB/Simulink® for simulation purposes. Together with the friction model from section 3 a state space representation is developed in section 4.

3. FRICTION MODEL

The Coulomb friction model (1) is well known and reflects the influence of the friction coefficient μ, which can depend on velocity, and the normal force between the two surfaces. When there is no movement the friction force is equal to the affecting one.

$$F_f = \operatorname{sgn}(\dot{x}) \cdot F_C = \operatorname{sgn}(\dot{x}) \cdot \mu \cdot F_N \qquad \dot{x} \neq 0 \tag{1}$$

Since the model can not reflect pre-sliding effects, which are important in nanometer scale, the elasto-plastic model [4,5] based on the bristle idea [6] and similar to the LuGre model [2,3] is utilised. The basic model is given by equations (2) and (3); equations (4) and (5) define the transition from elastic to mixed elasto-plastic movement. Equation (6) reflects the influence of the velocity which serves as a good method to adapt the sliding friction, but can hardly be proven since the maximum displacement of the bristles can hardly be evaluated during movements.

The influence of the normal load on a high-precision linear guide, equipped with a laser interferometer, was observed in [8]. As a result equation (6) is expanded by position and load dependent friction forces. The friction coefficients σ_0 and σ_1 could also depend on z.

$$F_f = \sigma_0 \cdot z + \sigma_1 \cdot \dot{z} + \sigma_2 \cdot \dot{x} \tag{2}$$

$$\dot{z} = \dot{x} \cdot \left(1 - \alpha(z, \dot{x}) \frac{z}{z_{ss}(\dot{x})} \right) \tag{3}$$

$$\alpha(z,\dot{x}) = \left\{ \begin{array}{cl} 0 & |z| \leq z_{ba} \\ 0 < \alpha_m < 1 & z_{ba} < |z| < z_{ss}(\dot{x}), \operatorname{sgn}(\dot{x}) = \operatorname{sgn}(z) \\ 1 & |z| \geq z_{ss}(\dot{x}), \operatorname{sgn}(\dot{x}) = \operatorname{sgn}(z) \\ 0 & \operatorname{sgn}(\dot{x}) \neq \operatorname{sgn}(z) \end{array} \right\} \qquad 0 < z_{ba} < z_{ss}(\dot{x}) \tag{4}$$

$$\alpha_m(z) = \tfrac{1}{2} \sin\left(\pi \frac{z - \frac{z_{ss} + z_{ba}}{2}}{z_{ss} - z_{ba}} \right) + \tfrac{1}{2} \quad \text{with} \quad z_{ba} \leq |z| < z_{ss} \tag{5}$$

$$z_{ss}(x,\dot{x}) = \frac{\operatorname{sgn}(\dot{x})}{\sigma_0} \left[F_C(x, F_N) + \left(F_S(x, F_N) - F_C(x, F_N) \right) e^{-\left(\frac{\dot{x}}{v_s}\right)^2} \right] \tag{6}$$

The pre-sliding domain can support fine positioning due to the large stiffness which decreases from its maximum in rest-position, but this also limits the dynamics due to the limited rate of force of the actuator. In the sliding domain there are small apparently random changes of the friction force during larger movements and velocities, which disturb exact path tracking especially with low velocities.

4. CONTROL

Control objectives are fine positioning, disturbance rejection, and exact path tracking as a basis for coordinated movements of multiple axes. Inputs of the system are references of actuator currents of the current controllers. The actuator force is proportional to the current, despite dynamics of the actuator and the influence of temperature and changes in the magnetic field. Measurements are only the x-y-positions and angles of the corner mirror located on the y-axis, so the other states must be reconstructed.

The path tracking properties of a PI state feedback controller with feed-forward path are compared with a robust double integrator controller according to [7]. All experiments are carried out with the simulation model according to sections 2 and 3 with respect to the real system inputs and outputs. The simulation model therefore contains also actuator and measurement dynamics including amplifier and measurement noise.

PI-State Feedback Regulator

Based on the mechanical model from section 2 and the linearised sliding friction model from section 3, a state space model is developed. Due to the fact that both axes are coupled not very strongly compared to the other dynamics, we here propose a decentralized control of both axes and present exemplary the x-control. The influence of the moving y-axis is taken into account as time-varying parameter, which is possible because the rate of change is very small compared to the other dynamics.

Equation (7) describes the influence of the y-position on the accelerated mass, while Equation (8) shows the overall system with the position of the tool-center-point x_{tcp} and the parallel position error δx as outputs of the system.

$$m_{E1}(x_3) = m_1 + \left(1 - \frac{x_3}{l}\right) m_3 \qquad m_{E2}(x_3) = m_2 + \frac{x_3}{l} m_3 \tag{7}$$

$$\begin{bmatrix} \dot{x}_1 \\ \ddot{x}_1 \\ \dot{x}_2 \\ \ddot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -\frac{c_{12}}{m_{E1}} & -\frac{\sigma_{2,1}}{m_{E1}} & \frac{c_{12}}{m_{E1}} & 0 \\ 0 & 0 & 0 & 1 \\ \frac{c_{12}}{m_{E2}} & 0 & -\frac{c_{12}}{m_{E2}} & -\frac{\sigma_{2,2}}{m_{E2}} \end{bmatrix} \begin{bmatrix} x_1 \\ \dot{x}_1 \\ x_2 \\ \dot{x}_2 \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ \frac{k_F}{m_{E1}} & 0 \\ 0 & 0 \\ 0 & \frac{k_F}{m_{E2}} \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \end{bmatrix}$$

$$\underline{y} = \begin{bmatrix} x_{tcp} \\ \delta x \end{bmatrix} = \begin{bmatrix} 1 - \frac{x_3}{l} & 0 & \frac{x_3}{l} & 0 \\ 1 & 0 & -1 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ \dot{x}_1 \\ x_2 \\ \dot{x}_2 \end{bmatrix} \tag{8}$$

Since the tool-center-point must be controlled, position and angle control around this point can be split into separate control tasks. Equations (9) state the calculation of the tool-center-point coordinates and the corresponding differential equation. The influence of the y-axis is handled as time-varying parameter, since the positioning distances are small compared to the operating range, and the system dynamics is fast compared to the rate of change of the x_3 position.

The state space model of the PI-state regulator is given by equations (10). Therefore we assume the integral angle controller to be affective, leading to perfect parallel feed.

$$\begin{aligned} x_{tcp} &= \left(1 - \frac{x_3}{l}\right) x_1 + \frac{x_3}{l} x_2 \\ \ddot{x}_{tcp} &= \left(1 - \frac{x_3}{l}\right) \ddot{x}_1 + \frac{x_3}{l} \ddot{x}_2 \end{aligned} \tag{9}$$

$$\begin{bmatrix} \dot{x}_{tcp} \\ \ddot{x}_{tcp} \\ \dot{e}_{tcp} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & -\frac{\sigma_{2,tcp}}{m_{E1}+m_{E2}} & 0 \\ -1 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_{tcp} \\ \dot{x}_{tcp} \\ e_{tcp} \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{k_F}{m_{E1}+m_{E2}} \\ 0 \end{bmatrix} (u_1 + u_2)$$

$$y = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_{tcp} \\ \dot{x}_{tcp} \\ e_{tcp} \end{bmatrix} \tag{10}$$

Figure 2 shows the state space model together with the control system, which basically consists of a reference generator, a feed forward part based on the reference trajectory, a parallel feed controller with an integrative part only, and a PI state feedback regulator based on the simplified system. The reference trajectory is smooth with respect to input and state constraints. Additionally the internal variable z is planned based on initial states and the reference trajectory.

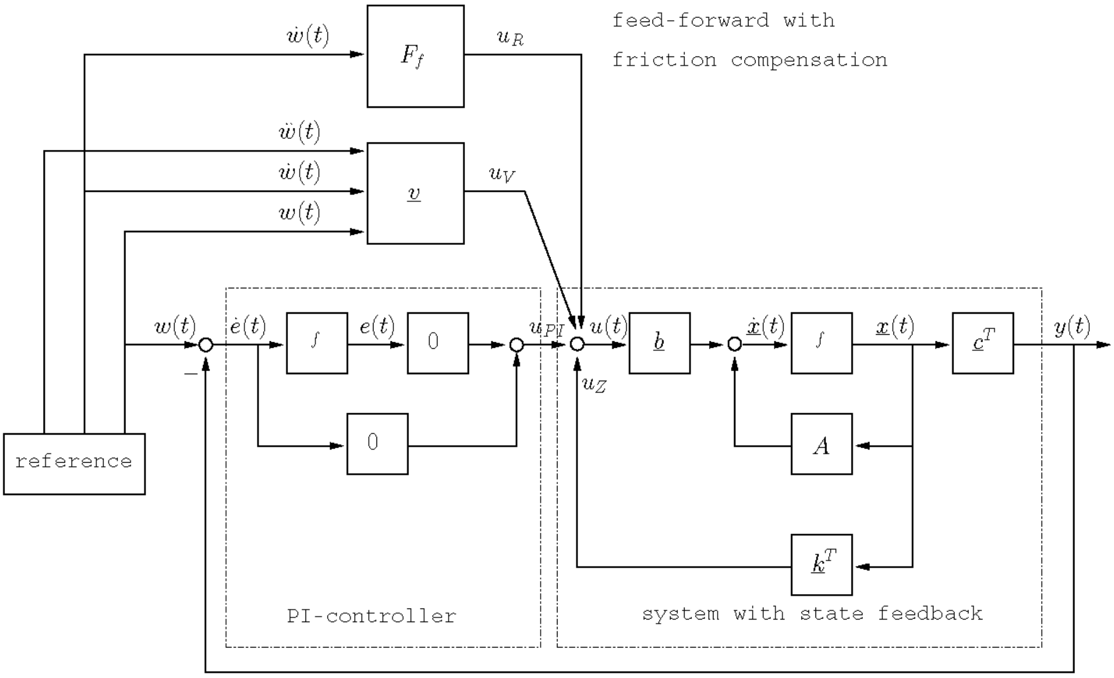

Fig. 2. State space model with PI-controller

Simulation results show that the PI-controller works well for fast direct movements due to the feedforward path and an integrative feedback. Especially when moving with small velocities the error dynamic is predictable well. For example a circle can be followed with a constant time delay leading to a synchronized movement with good accuracy. Figure 3 shows the positions, errors and feedback-forces for a circle with a diameter of 10µm and a movement time of around 750ms. The position errors are below 300nm/200nm and decrease to below 50nm/30nm outside direction-reversal domains.

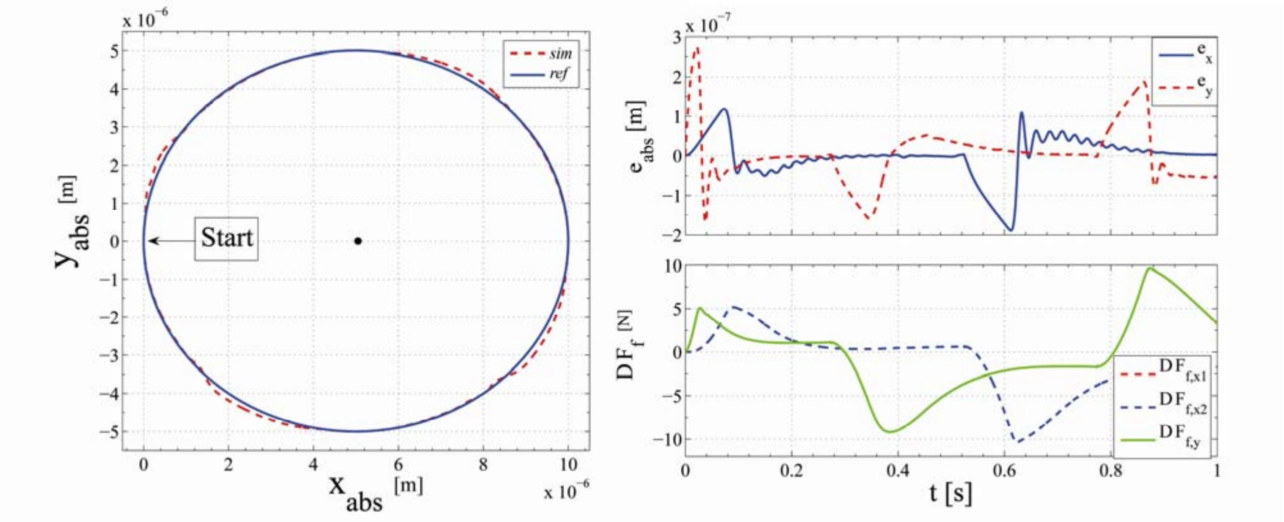

Fig. 3. Simulation results PI-state controller

Double Integrato Scheme

The double integrator controller was developed according to [7] and is shown in figure 4. Equation (11) denotes one simplified SISO axis with respect to time varying parameters and the total weight m of the axis. The calculated actuator force is divided into the two motor forces depending on the position of the y-axis by a decoupling feedforward.

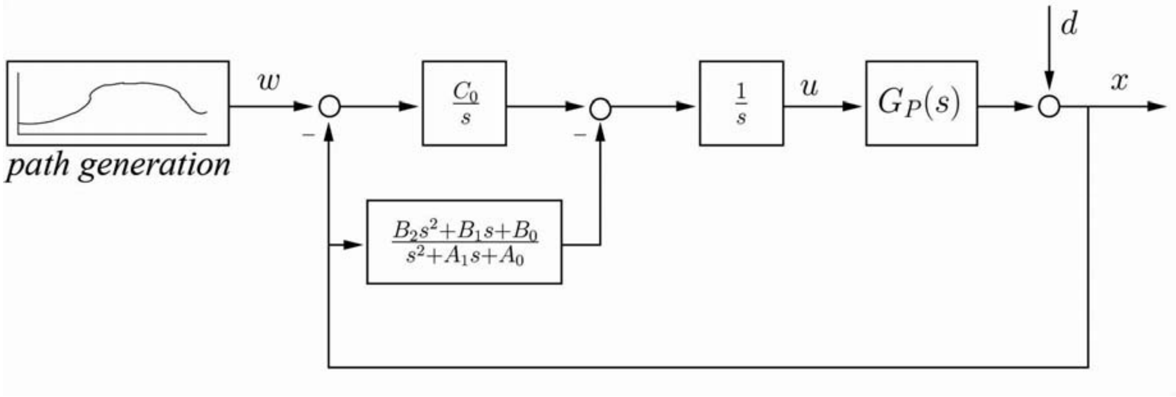

Fig. 4. Double integrator scheme [7]

$$G_P(s) = \frac{X_{tcp}(s)}{U_1(s)+U_2(s)} = \frac{\frac{1}{m}}{s^2 + \frac{\sigma_2}{m} s} \tag{11}$$

$$G_{DI}(s) = \frac{\frac{1}{m} C_0 \left(s^2 + A_1 s + A_0\right)}{s^6 + \left(\frac{\sigma_2}{m} + A_1\right)s^5 + \left(A_0 + \frac{\sigma_2}{m} A_1\right)s^4 + \left(\frac{\sigma_2}{m} A_0 + \frac{1}{m} B_2\right)s^3 + \frac{1}{m}\left(B_1 + C_0\right)s^2 + \frac{1}{m}\left(A_1 C_0 + B_0\right)s + \frac{1}{m} A_0 C_0} \tag{12}$$

$$G_{DI,P}(s) = \frac{\frac{1}{m} C_0 (s^2 + A_1 s + A_0)}{(s+p)^6} \tag{13}$$

Equation (12) denotes the transfer function of the controlled system according to figure 4. A coefficient comparison with equation (13) results in equations (16) which are used to calculate the controller parameters online with the given poles p.

$$A_0 = 15p^2 - 6\frac{\sigma_2}{m} p + \left(\frac{\sigma_2}{m}\right)^2$$

$$A_1 = 6p - \frac{\sigma_2}{m}$$

$$B_0 = \frac{84p^7 - 35\frac{\sigma_2}{m} p^6 + 6\left(\frac{\sigma_2}{m}\right)^2 p^5}{\frac{1}{m}\left(15p^2 - 6\frac{\sigma_2}{m} p + \left(\frac{\sigma_2}{m}\right)^2\right)}$$

$$B_1 = \frac{224p^6 - 90\frac{\sigma_2}{m} p^5 + 15\left(\frac{\sigma_2}{m}\right)^2 p^4}{\frac{1}{m}\left(15p^2 - 6\frac{\sigma_2}{m} p + \left(\frac{\sigma_2}{m}\right)^2\right)}$$

$$B_2 = \frac{20p^3 - 15\frac{\sigma_2}{m} p^2 + 6\left(\frac{\sigma_2}{m}\right)^2 p - \left(\frac{\sigma_2}{m}\right)^3}{\frac{1}{m}} \tag{14}$$

$$C_0 = \frac{p^6}{\frac{1}{m}\left(15p^2 - 6\frac{\sigma_2}{m} p + \left(\frac{\sigma_2}{m}\right)^2\right)}$$

Simulation results show that the double integrator controller works well for slow complex movements due to the high feedback gain for errors with low frequency. On the other hand measurement noise can be amplified easily and there is no feedforward path. Especially when moving with small velocities the tracking error is around the measurement noise. After a short initialisation phase of around 30ms nearly all smooth reference trajectories with respect to input constraints can be tracked with a small error. Figure 5 shows the positions, errors and friction forces for a circle with a diameter of 10µm and a movement time of around 750ms. The position errors are only below 500nm/300nm due to the high velocity, but decrease to below 10nm or even 5nm outside direction-reversal domains.

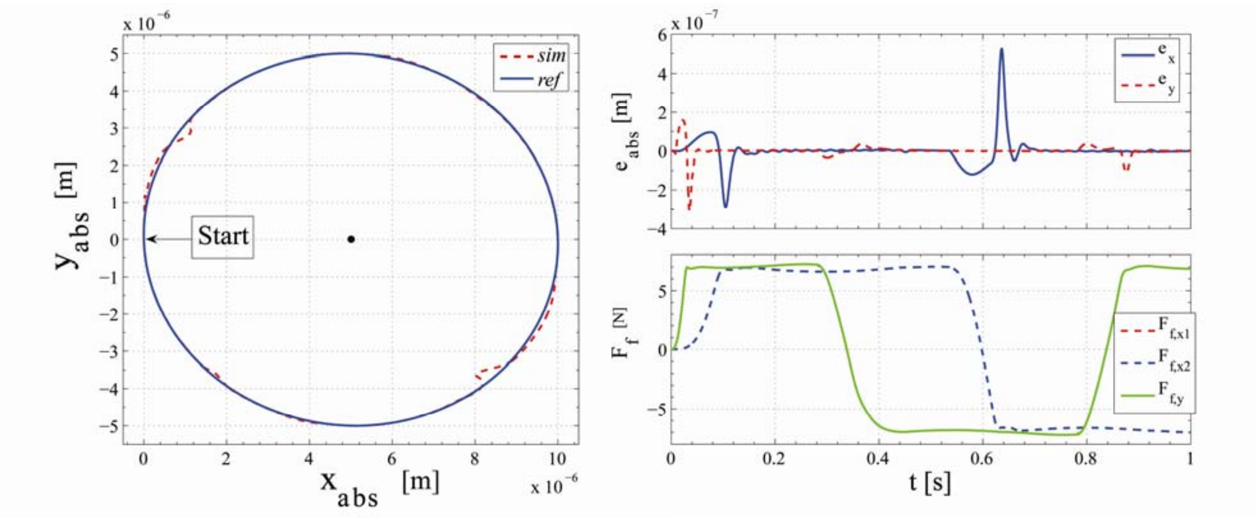

Fig. 5. Simulation results double integrator controller

4. CONCLUSIONS

In this paper a x-y-fine positioning table was modelled for simulation and control purposes. The friction model is based on former experiments with similar systems. In order to achieve exact path tracking of both axes the PI-state feedback regulator and the double integrator scheme were implemented. Finally both concepts are compared by using the developed simulation model. The PI controller is very fast and can be tuned well to achieve fast and exact fine positioning, which is ideal for positioning and step-height-measurements. The double integrator scheme is much more robust to low frequency disturbances and ideal for complex movements, which is ideal for scanning movements and three-dimensional tracking. In a next step the developed controllers will be tested with the experimental setup.

This work was supported by the DFG with the collaborative research center SFB622 ‘Nanopositionier- und Nanomessmaschinen’ and with the SPP1159 ‘New strategies of measurement and testing technology for the production of micro-system and nano-structures’. The authors would like to thank all those colleagues who have contributed to the developments described.

References:

[1] Hausotte, T. (2002). *Nanopositionier- und Nanomessmaschine*. Dissertation, Technische Universität Ilmenau

[2] Åström, K. J.; Canudas de Wit, C.; Olsson, H.; Gäfvert, M.; Lischinsky, P. (1998). Friction Models and Friction Compensation. *European Journal of Control*, **Vol. 29(4)**, pp. 176- 195

[3] Canudas de Wit, C.; Olsson, H.; Åström, K. J.; Lischinsky, P. (1995). A new Model for Control of Systems with Friction. *IEEE Transactions on Automatic Control*, **Vol. 40(3)**, pp. 419-425

[4] Dupont, P.; Armstrong, B.; Hayward, V.; Altpeter, F. (2002a). Single State Elastoplastic Friction Models. *IEEE Transactions on Automatic Control*, **Vol. 47(5)**, pp.787-792

[5] Dupont, P.; Armstrong, B.; Hayward, V. (2002b). Single State Elastoplastic Friction Models for Friction Compensation. *IEEE Transactions on Automatic Control 2001,* Article TP99-255 Revision 2002

[6] Haessig, D.; Friedland, B. (1990). On the modelling and simulation of friction. *Proceedings of the ACC San Diego 1990,* pp. 1256-1261

[7] Mao,Junhong;Tachikawa,Hiroyukietal. Double-Integrator control for precision positioning in the presence of friction, Tokio Institute of Technology,2003

[8] Zimmermann J., Sawodny O., Hausotte T., Jäger G.: *Friction* Modelling for Control of a Linear High-Precision Actuator, Mechatronics 2006 Heidelberg

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