Motion of a Micro/Nanomanipulator using a Laser Beam Tracking System *

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Abstract. This paper presents a study of the control problem of a laser beam illuminating and focusing a microobject subjected to dynamic disturbances using light intensity for feedback only. The main idea is to guide and track the beam with a hybrid micro/nanomanipulator which is driven by a control signal generated by processing the beam intensity sensed by a four-quadrant photodiode. Since the pointing location of the beam depends on real-time control issues related to temperature variation, vibrations, output intensity control, and collimation of the light output, the 2-D beam location to the photodiode sensor measurement output is estimated in real-time. We use the Kalman filter (KF) algorithm for estimating the state of the linear system necessary for implementing the proposed track-following control approach. To do so a robust master/slave control strategy for dual-stage micro/nanomanipulator is presented based on sensitivity function decoupling design methodology. The decoupled feedback controller is synthesized and implemented in a 6 dof micro/nanomanipulator capable of nanometer resolution through several hundreds micrometer range. A case study relevant to tracking a laser-beam for imaging purposes is presented.

1 Introduction

High-precision position measurement systems based on laser beam reflection and/or transmission are commonly used in nanorobotics applications. It is composed of the optical detecting set, including the laser diode (LD), the position-sensitive detector (PSD), alignment mechanisms, and the frame structure for maintaining the optical configuration. The general problem is to focus the beam in few micrometer size spots and to control actively the beam direction to stabilize the beam at a desired location. It is desirable in nanomanipulation tasks when focusing a near-infrared laser beam at a nerve cells leading edge [1],[2],

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when the laser beam perfectly tracks the moving atomic force microscope (AFM) probes [3] during manipulation tasks, or when the laser beam illuminates a microobject handled by a nanogripper for material characterization [4]. Usually, the laser beam calibration is time-consuming since the laser beam could be steered manually. Precise laser beam tracking of dynamic position with high-bandwidth rejection of disturbances produced by nanomanipulator platform vibration, piezoelectric actuator thermal drifts, photodetector noises, brownian motion of laser beam and atmospheric turbulence are critical for the success of micro and nanomanipulation tasks. As the single photodiode sensor is currently being used only for position measurement, the possibility of using it for feedback control is of great interest, since this might significantly increase the overall performance and reliability of nanorobotic systems. Recently, two laser beam tracking configurations are found based in the literature, i.e. steering the laser beam or the photodetector. In the first case, some works propose to use fast tilt two-axis steering mirrors based on electrostatic MEMS actuators [5] or piezoelectric actuators with a fixed four-quadrant PSD. In the second case, the PSD is driven by a dual actuation system with robot micro/nanomanipulators [6], or x-y linear positioning stages [7]. Whatever the technology involved, robust control of the laser beam tracking system is needed. The purpose of this paper is to design a control system that rejects disturbances in the sense of minimizing the variance of the error in the position of the laser beam. The main idea is to track the emitting beam by processing the maximum beam intensity sensed by a four-quadrant PSD mounted on a 6 dof dual-stage micro/nanomanipulator platform. Since the pointing location of the beam depends on real-time control issues related to disturbances, the laser beam position is estimated in real-time using the Kalman filter (KF) algorithm. To do so, a robust decoupled design controller is presented based on sensitivity function decoupling design methodology. The decoupled feedback controller is synthesized and implemented in a 6 dof coupled magnetic and piezoelectric manipulation platform.

The paper is divided into five sections. Section 2 describes the experimental setup. Section 3 describes the dynamics modeling and system identification procedure and results. Section 4 describes the decoupled control design structure. Section 5 presents experimental results for the performance of the beam steering system.

## 2 Experimental Setup

The control scheme of the beam pointing and tracking is shown in Fig.1. Two controllable micro/nano manipulators facing each other, composed of 3 d.o.f high-precision dual-stages, i.e., magnetic X-Y-Z closed-loop microstage (MCL Nano-Bio2M on the x-y-z axes) and piezoelectric x-y-z closed-loop nanostage (P-611.3S NanoCube from Physics Instruments), respectively. The coarse motion of the microstage is about few centimeters and the fine motion of the nanostage is about $100 \times 100 \times 100 \mu m$ positioning and scanning range comes in an extremely compact package. The laser source is mounted on top of the nanostage (right
manipulator) producing the laser beam. The main components of the beam steering experiment are a 635nm laser. A four-quadrant position sensing device (PSD) mounted on top of the nanostage (left manipulator) that measures the position of the image that the laser beam forms on a fixed plane. On the side view, a white light illuminates the workspace for top-view (top optical microscope - Mituyo ×50) and side-view (TIMM × 150) imaging. The sample platform is at rest during manipulation that is fixed on the system base.

Fig. 1. Experimental setup.

Fig. 2 shows the overall control scheme for power, laser beam tracking and micro/nano manipulator control. The laser beam motion control (Brownian or stochastic trajectory) and measurement sequences are processed in real-time using MATLABs xPC software with a stand alone target machine operating at a sample-and hold rate of 2kHz. A data acquisition (DAQ) (NI 6289) card is used for highspeed capturing of photodiode voltage output from a lock-in to detect laser beam intensity maximum and beam tracking. A multi-thread planning and control system is developed to independently manage the coordination during parallel laser beam motion and tracking, respectively.

3 Dynamics Modeling

This section reviews the different model dynamics of the different system components.
3.1 Dynamics of Piezoelectric and Magnetic Actuators

The piezoelectric 3-dof nanostage and the magnetic 3-dof microstage are deemed as three-input and two-output systems. We identified the dynamics of our dual micro/nano manipulators in x-y-z-directions using their responses of pseudo random binary sequence. The dynamic model is characterized by the following transfer functions:

\[
G_{\text{micro}(x,y,z)}(z) = \frac{b_0 + b_1 z^{-1} + b_2 z^{-2} + b_3 z^{-3}}{1 + a_1 z^{-1} + a_2 z^{-2} + a_3 z^{-3}}
\]

\[
G_{\text{nano}(x,y,z)}(z) = \frac{b_1 z^{-1} + b_2 z^{-2} + b_3 z^{-3}}{1 + a_1 z^{-1} + a_2 z^{-2} + a_3 z^{-3}}
\]

3.2 Dynamics of Four Quadrant Detector

A four quadrant photo sensitive detector (PSD) has four photosensing parts arranged in four quadrants, respectively. When the elements are lighted by a beam of laser, they will generate currents according to the light intensity and then amplified into voltage signals. The combinations of voltages \(V_1\) to \(V_4\) can be used to indicate the offsets of the spot in relation to the center of the PSD as follows:

\[
V_x = (V_1 + V_4) - (V_2 + V_3) \\
V_y = (V_1 + V_2) - (V_3 + V_4) \\
V_s = V_1 + V_2 + V_3 + V_4.
\]
The $V_x$ and $V_y$ channel outputs are directly related to the energy of the laser beam that falls in each quadrant while $V_s$ is the sum voltage. It is assumed that the light intensity on the laser’s beam cross section obeys Gaussian distribution. The current generated by each sensing element can be described as given in:

$$I = k_1 \int \int \frac{2E_t}{\pi r^2} e^{\frac{-(x_1^2 + y_1^2)}{r^2}} dx_1 dy_1$$

where $I$ is the current, $r$ the radius of the laser light spot, $E_t$ is the energy of the laser beam, $(x_1,y_1)$ is the coordinate of a point on the light spot in a coordinates system located at the center of the light spot, and $k_1$ is a coefficient. As shown in Fig.3, in the operation region (small neighborhood of the aligned location), the photodiode voltage output $V_x$ is approximately linearly related to light intensity units, with a negative slope. As the curve $V_y$ is similar to that, it is omitted here. Obviously, when the spot is located in the sensing surface $V_x \neq 0, V_y \neq 0$ while if the spot is located in the center $V_x = 0, V_y = 0$.

As we can see in Fig.4, the experimental intensity sensed by the PSD can be fitted with a Gaussian distribution as calculated by the theoretical equation (4).

### 3.3 Dynamics of Laser Beam Position

The laser beam motion is assumed similar to the Brownian motion (represented in Fig. 5) of a particle subjected to excitation and frictional forces. The Brownian motion is given by the generalized differential equation:

$$\frac{d^2x(t)}{dt^2} + \beta_x \frac{dx(t)}{dt} = W_x$$

![Fig. 3. Output voltage curve $V_x$ with a zoom in the block area near zero on an four-quadrant PSD.](image)
Fig. 4. Light intensity on the laser’s beam cross section: (left) theoretical and (right) experimental intensity obeying to Gaussian distribution.

Fig. 5. Particle Brownian motion

were $\beta_x$ coefficient of friction and $W_x \sim N(0, \delta_x^2)$. To estimate with a discrete filter the laser beam positions at each sampling time $t_k$, a discrete model of the continuous dynamic (4) is necessary. In the $x$-axis the discretized equations of motion using a zero-order hold(zoh) are given by:

$$\dot{x}_k = \frac{x_k - x_{k-1}}{\Delta T}; \quad \ddot{x}_k = \frac{\dot{x}_k - \dot{x}_{k-1}}{\Delta T}$$

(5)

from (4) and (??) we obtain:

$$\dot{x}_k = \frac{\dot{x}_{k-1} + \Delta T W_{x_k}}{1 + \beta_x \Delta T} = a_x \dot{x}_{k-1} + b_x W_{x_k}$$

(6)
where $\Delta T$ is the discretisation time step and the statistic properties of the excitation $W_{x_k}$ force is assumed to be an zero-mean Gaussian random variable with variance $\delta^2_x$. The $y$-axis can be modeled in the same manner as the $x$-axis, though with different dynamics. For 2D representation, the source state at discrete time $k$ is defined as

$$[x_k \ y_k \ \dot{x}_k \ \dot{y}_k]^T$$

(7)

$(x_k, y_k)$ and $(\dot{x}_k, \dot{y}_k)$ are the source portion in the plane $x$-$y$ and velocity respectively. The discrete state space of the Brownian laser beam is represented by:

$$X_k = AX_{k-1} + BW_k$$

(8)

$$Y_k = CX_{k-1}$$

(9)

The state representation matrices $(A, B)$ are derived from the particle dynamics defined in (5)-(6) and $W_k \sim N(0, Q)$ is an zero-mean Gaussian random variable with matrix variance $Q$. It comes from (8) that:

$$X_k = \sum_{i=1}^{k} A^{k-i} BW_i + A^k X_0$$

(10)

Because successive random variables $W_i$ form apriori discrete zero mean white Gaussian process, $X_k$ form (10) is Gaussian if the knowledge on $X_0$ is assumed Gaussian or equal to some fixed value. Its a priori variance at each step $k$ can be calculated :

$$\sigma^2(X_k) = \sum_{i=1}^{k} A^{k-i} B \sigma^2(W_i) + A^k \sigma^2(X_0)$$

(11)

(11) shows that bigger is the variance of $W_k$ to set and bigger is the a priori uncertainty variance on the possible values of the modeled unknown position of the beam laser at $t_k$. Finally, the measurement $Y_k$ of position takes into account the discrete-time white Gaussian noise $V_k$ white zero mean and Variance $R$ added by the four quadrant photosensitive detector.

$$Y_k = CX_{k-1} + V_k$$

(12)

4 Control Scheme of Beam Pointing and Tracking

The problem considered is that of tracking a laser beam into the $x$-$y$ plane by robust control issues of the dual micro/nano manipulators motions, and the localization of the current laser beam position [8]. It implies to integrate a prediction model that anticipates the a priori laser beam motion, taking into account both dynamics of the beam laser and manipulators models. Figure 6 presents the master-slave control scheme adopted for dual stage to control two independent outputs of micro manipulator $G_m$ and nano manipulator $G_n$ by only one position feedback signal that includes the contribution of both manipulators to track laser beam motion by high precision.
Fig. 6. Master-slave controller with decoupling structure for maximum light tracking.

4.1 Kalman Filter Estimator

In robotics, the Kalman filter is most suited to problems in tracking, localization, and navigation, and less so to problems in mapping[1][2]. This is because the algorithm works best with well-defined state descriptions (positions, velocities, for example), and for states where observation and time-propagation models are also well understood. The prediction-estimation stages of the Kalman filter are derived from equations (8) and (12):

**Prediction.** A prediction $\hat{X}_{k|k-1}$ of the state at time $k$ and its covariance $P_{k|k-1}$ is computed according to:

$$\hat{X}_{k|k-1} = A\hat{X}_{k-1|k-1} + BU_k$$  \hspace{1cm} (13)

$$P_{k|k-1} = AP_{k-1|k-1}A^T + Q(k)$$  \hspace{1cm} (14)

**Update.** At time $k$ an observation $y(k)$ is made and the updated estimate $\hat{X}_{k|k}$ of the state $X_k$, together with the updated estimate covariance $P_{k|k}$, is computed from the state prediction and observation according to:

$$\hat{X}_{k|k} = \hat{X}_{k|k-1} + K_k(y_k - C_k\hat{X}_{k|k-1})$$  \hspace{1cm} (15)

$$P_{k|k} = P_{k|k-1} - K_kS_kK_k^T$$  \hspace{1cm} (16)

where the gain matrix $K_k$ is given by:

$$K_k = P_{k|k-1}C_kS_k^{-1}$$  \hspace{1cm} (17)

where

$$S_k = C_kP_{k|k-1}C_k + R_k$$  \hspace{1cm} (18)

is the innovation covariance. The difference between the observation $Y_k$ and the prediction observation $C_k\hat{X}_{k|k-1}$ is termed the innovation or residual $r(k)$. Thus the input of the Kalman filter is the noisy measurement of the laser beam displacement in the $x$-$Y$ direction delivered by the photodiode detector and $\hat{X}_k$ is the output of the filter representing the estimation of the displacement at time $t_k$. 
Fig. 7. Experimental tracking with Kalman filter: Motion estimation along $x$-$y$ axis with corresponding errors and 2D displacement.
4.2 State estimation

In order to evaluate the performance of Kalman filter we give to the laser beam a synthetic trajectory generated randomly. The data rate of the sensor is $\Delta T = 2$. The Kalman filter parameters, i.e measurement noise matrix $R$, process noise matrix $Q$ and initial state error matrix $P_0$, where chosen as:

$$Q = 10^{-2}I_{4 \times 4} + \begin{bmatrix}
0 & 2b_x^2 & b_x & b_x \\
2b_x^2 & 0 & b_x^2 & b_x^2 \\
b_x & b_x & 0 & 2b^3 \\
b_x & b_x^2 & 2b^3 & 0
\end{bmatrix}$$

$$R = 10^{-4}I_{2 \times 2};$$

The noise matrices were chosen empirically in order to achieve the best performance of the filter. The results of laser beam motion prediction using Kalman filter are presented in fig.7. At first glance, the filter succeed to follow the true trajectories very closely. As illustrated the performances of the Kalman filter in terms of precision the filter converge to the real position of the laser beam with a minimal error.

5 Experiments

In order to validate experimentally the simulation results, we presents in the following different experimental results. In a first step, the laser beam positioning is initiated automatically by moving linearly the laser beam until to be detected by the PSD. After detection, the maximum intensity provided by the PSD is computed by eq(4) and feedback to the $x$-$y$-$z$ nanostage for local maximum search (see Fig.8). In a second step, a composite signal (constant displacement and Brownian motion) is sent to the laser beam micro/nano manipulator. The results of a typical tracking run for a fast composite signal is shown in Figures 9. It should be noted that this approach assumes variations of laser light intensity during motion, measurement noise, high motion dynamics. The results
demonstrate the robust estimation of the laser beam position is a real time way. As expected, the filtered estimates exhibited a smaller variation. Furthermore, the master-slave controller with decoupled sensitivity is optimized in terms of tracking error as illustrated in the figures.

Fig. 9. Experimental tracking with Kalman filter: Motion estimation along $x$-$y$ axis with corresponding errors and 2D displacement.
6 CONCLUSIONS AND FUTURE WORKS

This paper has presented a study of the control problem of a laser beam illuminating and focusing subjected to dynamic disturbances using light intensity for feedback only. The main idea is to guide and track the beam with a hybrid micro/nanomanipulator which is driven by a control signal generated by processing the beam intensity sensed by a four-quadrant photodiode. The simulations and experiments demonstrated the efficiency of the approach when submitted to external disturbances. The use of the Kalman filter (KF) algorithm for estimating the state of the linear system necessary for implementing the proposed track-following control approach as been proven to be efficient at high dynamics. Further work will be carried out on nanomanipulation of objects under the field of view of a focus laser beam.

References