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Tracking Controls of a Laser Positioning System

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Abstract

Laser Positioning System (LPS) is a type of coordinate measuring systems that can measure positions of a small and easily movable target generally mounted with a retroreflector. LPS operates by orienting a motor-driven mirror to direct a laser beam to the center of the retroreflector. When the retroreflector moves the LPS must keep the laser pointed at the center. This is done by measuring the offset of the laser beam entering the retroreflector and the reflected beam using a Photo Sensitive Detector (PSD) and adjusting the mirror orientation accordingly. This paper discusses control systems and control laws for this tracking task used by an LPS prototype built at Chulalongkorn University. The proposed controller composes of a PD inner-loop closed with an encoder signal and a PI outer-loop closed with the PSD signal. Experimental results are given in terms of tracking speed at 0.5 m and a maximum tracking range. After a further investigation, however, it was found that the open loop gain of the system is highly affected by the distance of the retroreflector. To allow full flexibility of the system, this paper also discusses methods of adjusting the control gain without directly measuring the retroreflector distance. Two methods were proposed and preliminary simulation results are provided.

Keywords: Laser Positioning System, Control System Designs, Tracking Controls

1. Introduction

In a typical robotic manufacturing, design and production of jigs and fixtures constitute a significant portion of the manufacturing cost. This is mainly because, although motions of manufacturing robots are highly repeatable, they have low accuracy [1]. Workpieces must be hold rigidly in a fixed location to exploit repeatability of the robots. As a result, jigs and fixtures, which are generally custom made for each product, are essential.

In order to reduce the fixture cost, a manufacturing technique called “Fixtureless Robotics Manufacturing” is being developed at Chulalongkorn University. In the study, a workpiece is assumed to be hold rigidly (by a low cost universal fixture), however it will arrive at the manufacturing cell with unknown position and orientation. Once arrived, the position and orientation of the workpiece will be measured using a Laser Positioning System (LPS). This data allows the robot to work on the workpiece regardless of the location of the workpiece. The LPS was also proposed for measuring the robot’s end-effector directly to improve the accuracy of the robot. As such, the LPS system is the key component of the fixtureless manufacturing technique. An example of the fixtureless manufacturing cell is shown in Figure 1. The system might employ a single station LPS (using interferometer to measure distance) or a two station LPS. A few LPS prototypes were made and are being made at Chulalongkorn University [2].

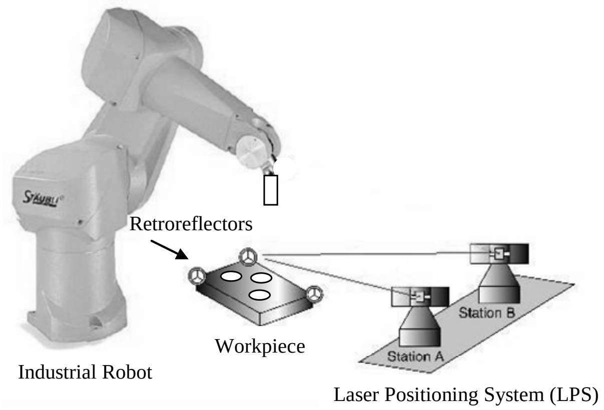

Figure 1, A fixtureless robotic manufacturing system.

This paper will focus on the control issues of this LPS system. Laser Positioning System (LPS) is a type of coordinate measuring systems that can measure positions of a small and easily movable target generally mounted with a retroreflector. For a continuous operation, LPS must be able to keep the laser pointed at the retroreflector as it moves to various measuring positions. This is done by measuring the offset of the laser beam entering the retroreflector and the reflected beam using a Photo Sensitive Detector (PSD) and adjusting the mirror orientation accordingly. This paper discusses control systems and control laws for this tracking task. Two types of control laws were tuned experimentally using PID controllers. The first use only the PSD signal to close the loop while the second use both the PSD signal and the mirror angle measurement to close the loop.

Furthermore, it is found that the open loop gain of the system is highly affected by the distance of the retroreflector. As the system operates, the open-loop gain of the system can vary as much as 10 times of the minimum value. The distance can be measured using an interferometer and can be used to adjust to control gain

[3]. The interferometer is, however, very expensive. If LPS is used only to measure a stationary object such as the workpieces, it is possible to use only one LPS system without using the interferometer. Position of a stationary retroreflector can be found by triangulation using only a single movable LPS system, which is also under development at Chulalongkorn University. Similarly, a system with two LPSs (triangulation) may not have the distance value at all times, especially at the beginning of their operation where each LPS must be brought to point at the retroreflector one system at a time. As a result, to allow full flexibility of the LPS system, this paper also discusses methods of adjusting the control gain without directly measuring the retroreflector distance. Two methods for adjusting the control gain are proposed. Simulation results are given in this paper.

2. LPS prototype

Typical components of an LPS system required to track a retroreflector are shown in Figure 2. To track the retroreflector, the system adjusts the tracking mirror to direct a laser beam to the center of the retroreflector. When the retroreflector moves, the LPS must keep the laser pointed at the center. This is done by measuring the offset of the laser beam entering the retroreflector and the reflected beam using a Photo Sensitive Detector (PSD) and adjusting the mirror orientation accordingly.

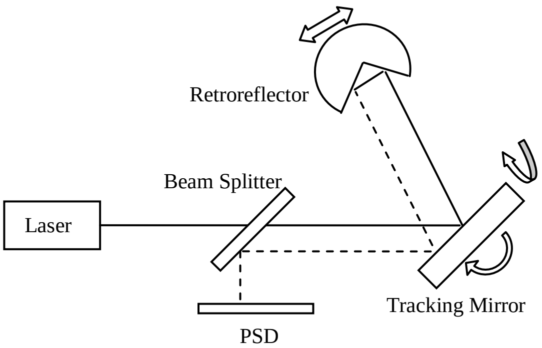

Figure 2, Tracking components of an LPS.

An LPS prototype is shown in the Figure 3. The followings are some details of the components (for more information please see [2]). The mirror is adjusted using two motors with no transmission. The azimuth motor is a 80W brushless DC motor from Maxon motor (EC32) with a maximum torque of 355 mN-m and the altitude motor is a 17W brushless DC motor from Computer Optical Product (CM335) with a maximum torque of 232 mN-m. The mirror and the altitude motor are mounted on a platform that can be rotated by the azimuth motor. Angular positions of the two motor are measured using the CM335 motor/encoder sets. The encoders are sine wave encoders with 2048 cycles/rev. Square waves are generated from these signals at 2048 cycle/rev for commutation by power amplifiers which are running in current mode with a 1 KHz bandwidth. With interpolation, the sine wave signal is used to measure position with accuracy around 8×10^{-3} degree or 47000 pulse/rev [2]. The retroreflector has an opening of 0.25 inch and the PSD have a working area of 10×10 mm.

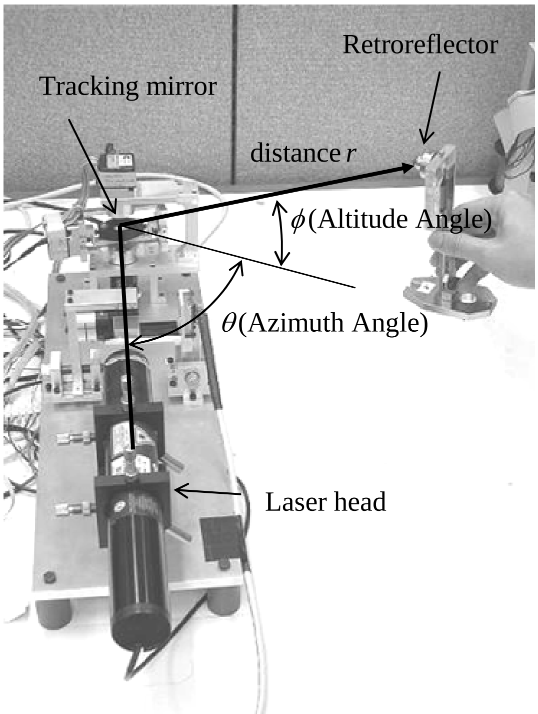

Figure 3, An LPS prototype.

3. Control design

Two types of control laws were studied: a single loop system and a two-loop system. The schematic of the control system is shown in Figure 4. For a single loop system, the angular position encoder is not used, $C_1(\mathbf{s}) = 1$ and $C_2(s)$ is a PID controller. For the two-loop system, the controller $C_1(s)$ and $C_2(s)$ are PID controllers.

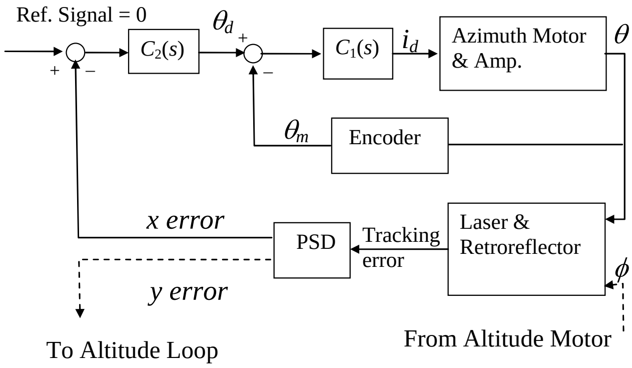

Figure 4, Control system schematic.

3.1 The single loop controller

Evaluation of the single loop controller was performed using only the azimuth motor (with the altitude motor fixed). Performing a number of experiments, it was found that a PD ($C_2(s)$) controller performs best. An experimental result is shown in Figure 5. In this experiment, the retroreflector was fixed at 1 meter and a reference signal asking for an azimuth offset (x error in Figure 4) of the laser from the center point of the PSD was used instead. Note that the error at the retroreflector is only half of this value. As seen in Figure 5, the rise time of the response is around 12 msec and the settling time is 65 msec. However, the overshoot is 25% and 75% depending on which way the movement was.

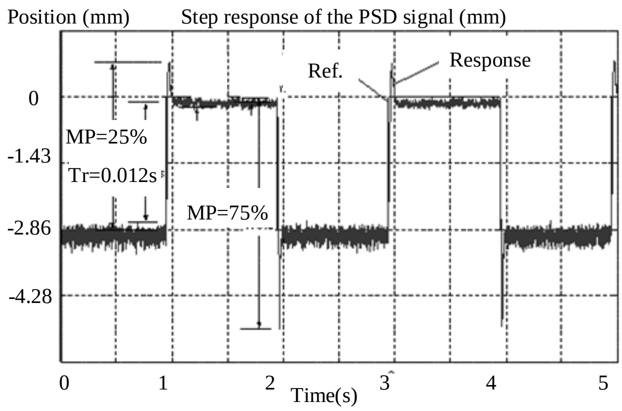

Figure 5, Step response of the PSD signal.

Using this PD controller, the maximum distance of the retroreflector was found to be less than 2 m which is significantly smaller than the 5 m goal. It was found that the system is highly oscillatory at the distant around 2 m. One of the reasons is that the PSD signal is rather noisy. Hence, *Kd*, the derivative gain, in the PD controller cannot be set higher to provide more damping. Hence *Kp*, the proportional gain, must be kept small to avoid excessive overshoot which is necessary to keep the laser from falling off the retroreflector. As a result, the motor in this system is quite sensitive and cannot hold the mirror even against a small disturbance. When touch lightly at the mirror, the mirror can be knock off the desired orientation. One can feel that the motor does not provide enough torque against disturbance to hold the mirror in place. As a result, another type of controller was investigated to reduce these shortcomings.

3.2 The two-loop system

The two-loop system is shown in Figure 4. Tuning of the controller was done for the inner-loop first. Figure 6 and 7 are the step response of the azimuth angle and the altitude angle to a 1 degree step command. A suitable controller was found to be a PD controller ($C_1(s)$). Again, the system still suffers from limited *Kd* (derivative gain of the PD controller) due to the fact that only position measurements are available. Then, the outer-loop was tuned. Figure 8 and 9 show the step response of the laser location on the PSD (0.1 volts or approximately 0.5mm step). The outer-loop controller is a PI controller where K_I (the integral gain) dominates. The tuning was done with the retroreflector at the distance of 0.5m.

Tracking range and tracking speed were measured. The maximum range was found to be 5 m (with interpolated encoder signal). The maximum speed is 0.6 m/s when the retroreflector is moving primarily in the azimuth direction at distance of 0.5m. The tracking speed is, however, significantly less then the goal of 4 m/s.

After a closer inspection, two problems were found. The first is that the regulation performance of the altitude motor is much worst than that of the azimuth motor. As a result, the tracking performance is limited by the performance of the altitude loop. It was found that the altitude regulation is oscillatory as shown in Figure 10. In the figure, location of the return laser on the PSD when the retroreflector is not moving is plotted (0.1 volt corresponds to approximately 0.5mm). Clearly, the altitude regulation is much more oscillatory (the *y* direction). A new LPS prototype is being made to reduce this problem.

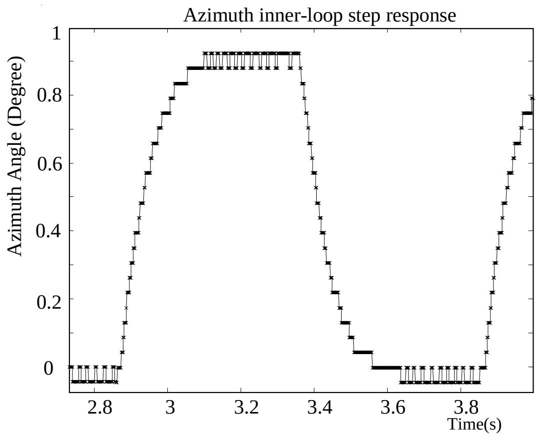

Figure 6, Step response of the azimuth inner-loop.

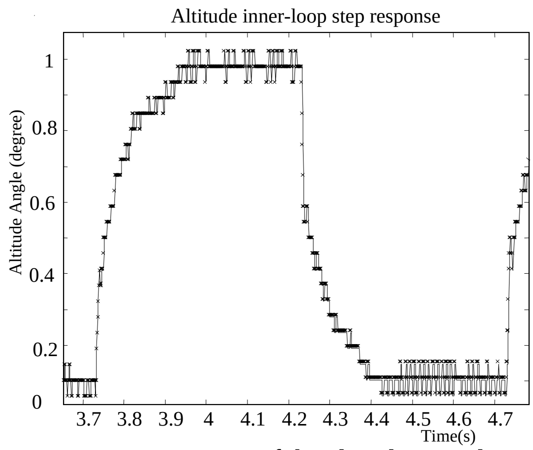

Figure 7, Step response of the altitude inner-loop.

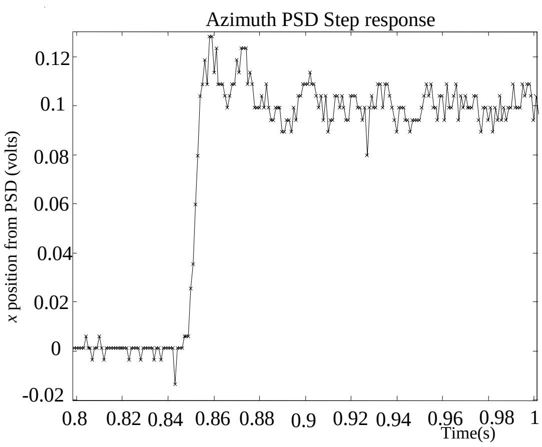

Figure 8, Step response of the azimuth PSD voltage.

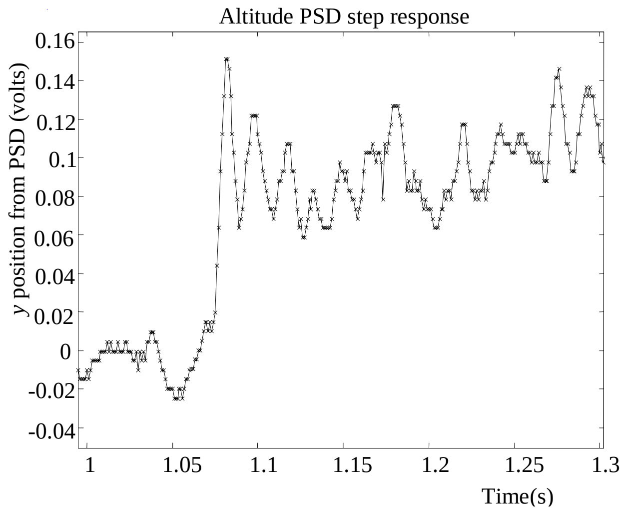

Figure 9, Step response of the altitude PSD voltage

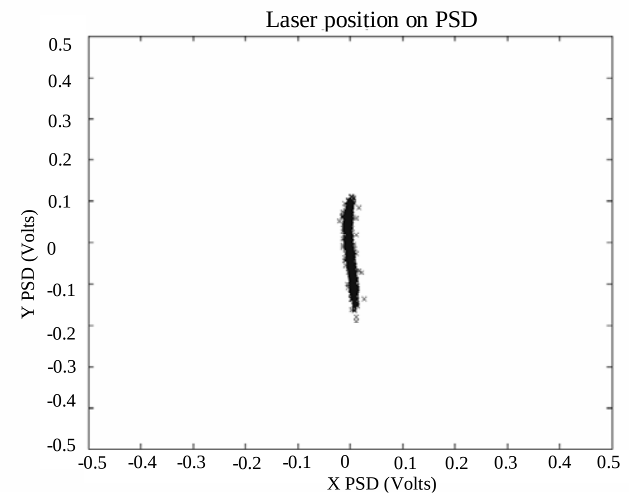

Figure 10, Laser position of the PSD

The second problem found was that the open loop gain of the system is highly affected by the distance of the retroreflector. As the system operates the open-loop gain of the system can vary as much as 10 times of the minimum value. This results from the distance of the retroreflector to the tracking mirror which can vary from near zero to 5 meters and the fact that a degree rotation of the mirror causes the reflected laser beam to turn by two degrees. In particular, the loop gain of the closed-loop system has a factor of 2*R*, where *R* is the distance of the retroreflector to the tracking mirror. In the experiments, it was convenient to use a higher value of K_P (in C_2(s)) when the retroreflector is closed and to use a smaller value otherwise.

4. Distance adaptation

The distance of the retroreflector are generally used in the control law to compensate for the difference of the loop gain resulting from the distance of the retroreflector [3-5]. As stated in the introduction, it is desirable to design a system that can adjust the K_P automatically without actually measuring the distance. This section discusses two approaches to solve this problem. However, only preliminary simulation results (with only one degree of freedom mirror motion) are available at this point.

4.1 Distance estimation

Standard recursive least-square technique was applied to estimate the distance *R* of the retroreflector and the tracking mirror. Figure 11 shows related parameter. In the figure, the distance of the retroreflector from the tracking mirror is *R*, the desired direction of the laser beam is θ_d, the actual direction is θ, the mirror orientation is θ_m ($\theta = 2\theta_m$), and the error of the laser from the center of the retroreflector is *d* (twice of this error shows up on PSD).

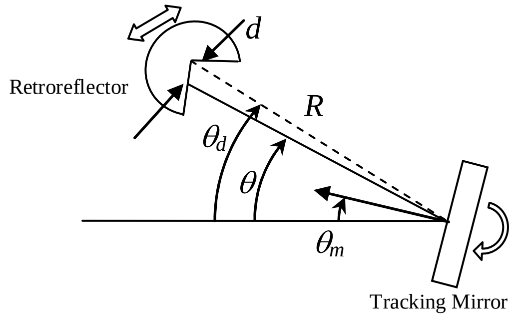

Figure 11, Parameters related to the estimation fo the distance (*R*).

Since the tracking mirror is controlled to keep θ close to θ_d, it can be approximated that

$$d = R\,(\theta_d - \theta) \qquad (1)$$

Assuming that *R* and θ_d change only slowly, they can be estimated by using *d* and θ. To apply a discrete-time recursive estimator, Eq. (1) is written as

$$y(k) = \varphi^T(k)\,\alpha(k) \qquad (2)$$

where *k* is used to indicate the k^{th} time step, $y(k) = d(k)$, $\varphi^T(k) = [1 - \theta(k)]$, $\alpha(k) = [R\theta_d(k), R(k)]^T$. Let $A = [a, b]^T$ where *a* is an estimate of $R\theta_d$ and *b* is the estimate of *R*, the recursive least-square estimator with exponential forgetting factor is given by [6]

$$\begin{aligned} A(k) &= A(k-1) + K(k)(\,y(k) - \varphi^T(k)A(k-1)\,) \\ K(k) &= P(k-1)\,\varphi(k)(\,\lambda - \varphi^T(k)\,P(k-1)\,\varphi(k)\,)^{-1} \\ P(k) &= (\,I - K(k)\,\varphi^T(k)\,)\,P(k-1)/\,\lambda \end{aligned} \qquad (3)$$

where λ is the exponential forgetting factor.

When *R* and θ_d are constants, it is easy to show that the estimator in Eq. (3) can be used to estimate both *R* and θ_d. Figure 12 shows the time trajectory of the estimates of a simulation. In this simulation, $\theta(t)$ is a signal generated by passing a pulse train with the amplitude of 0.01pi/180 and frequency of 1 rad/sec through a filter F(s) = 1/(s/0.1+1), λ = 0.9, *P*(0) = [2,1;1,2], *a*(0) = *b*(0) = 1, R = 3, θ_d = 0, sampling time of the estimator is 0.01 sec. Clearly, the estimate converged as expected.

In actual application, however, R and θ_d are not constants. Furthermore, θ is controlled using d to follow θ_d as much as possible. In simulation, it was found that R and θ_d can only vary very slowly. For example, if θ is assumed to be controlled such that θ_d as $\theta(s) = F(s)\theta_d(s)$, R and θ_d can vary only as slowly as from 3 to 3.5 m and from 0 to 0.1 degree in 50 second, respectively. Furthermore, an excitation signal (a band limited white noise filtered with $F(s)$) must also be added to $\theta(t)$ to allow the estimator to work as desired. Figure 13 shows the time trajectory of the estimates in this case.

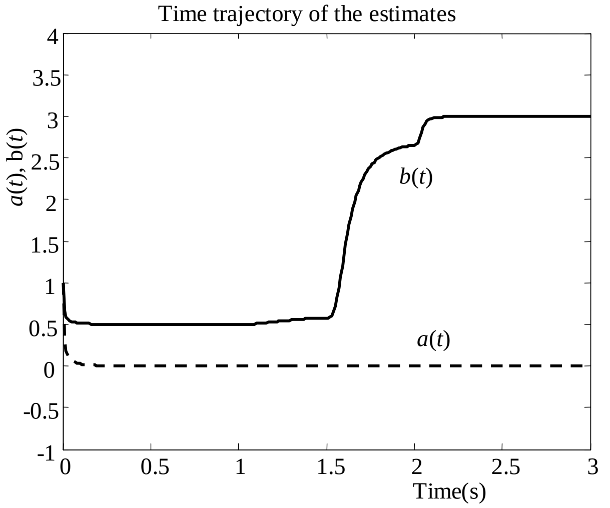

Figure 12, Time trajectory of the estimates when R and θ_d are constants

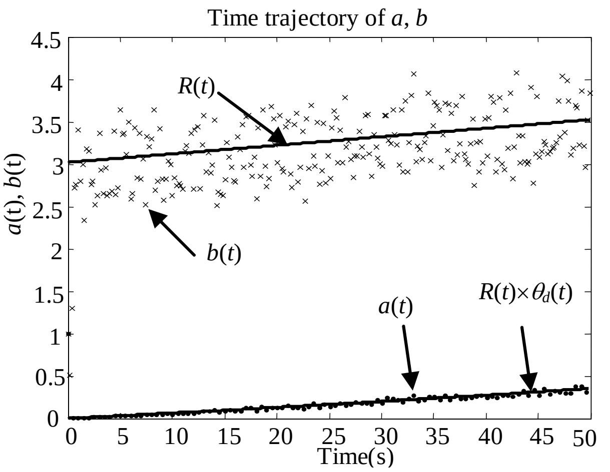

Figure 13, Time trajectory of the estimates when R and θ_d are not constants

In this figure, $\lambda = 0.7$, $P(0) = [2,1;1,2]$, $a(0) = b(0) = 1$, sampling time of the estimator is 0.01 sec, and the band-limited white noise added was generated at 0.01 sampling time and with the power of 1e-7.

Based on this simulation results, this method based on estimating R is not expected to perform well in actual applications. While adding the excitation signal improves the estimates, it is not desirable because it may cause the laser to fall off the retroreflector. In fact, when R is large, only small variation in the laser direction is acceptable.

4.2 Direct adaptation

Another approach investigated is similar to the direct adaptive control technique [6]. In particular, the controller gain is adjusted to compensate for changes in the distance of the retroreflector in order to fix the loop gain at a fixed value. This is done by trying to set up an indicator for the loop gain of the system and adjust the control gain such that this indicator is at a desired value.

The following is proposed. By feeding the system output to a lightly damp 2nd order filter with poles around the desired closed-loop pole of the system, the output of this 2nd order filter can be used to as an indicator of how much the system's loop gain differs from the desired value. The controller's gain is then adjusted in order to move the loop gain closer to the desired value. The idea is similar to that of [7] but is in a more simple form.

To show that the method can be applied, a simulation is performed as follows. The two loop control system in Figure 4 is used but only with the azimuth motor. The motor transfer function is (K_m/d) / ($(s/\tau + 1)(J/bs^2 + s)$) where Km = 0.0205, $\tau = 1000\times2\pi$, $J = 6\times10^{-4}$, b = 3.4×10^{-6}. The Laser and PSD are modeled with a gain of $2R$. The encoder is a unity gain. The controller $C_1(s)$ and $C_2(s)$ are tuned as described in section 3.2. $C_1(s)$ is a PD controller with $K_P = 100$ and $K_D = 5$ and $C_2(s)$ is a PI controller with $K_P = 0.04$ and $K_I = 200$. The inner-loop has rise time ≈ 0.1 sec. (compared to 0.13 in Figure 6) and %overshoot = 0% and the outer-loop has rise time ≈ 8 msec. (compared to 3.3 msec. in Figure 8) and %overshoot ≈ 30% (compared to 30% in Figure 8). The tuning was done with $2R$ = 1 m.

Using these gains, the closed-loop transfer function can be found to have a pair of under damped poles at $-78.6 \pm 172i$. The PSD signal is then feeds to a 2nd order filter with a unity DC gain and with two poles at $-3 \pm 172i$. The output of this system is squared and used as the indicator, *ind*. Let's factoring out a gain K to be adapted from $C_2(s)$ and set its nominal value to be 5. Figure 14 shows the maximum value of *ind* as a function of the gain ($K\times2R$) when the reference signal is a pulse train with amplitude of 0.005 m.

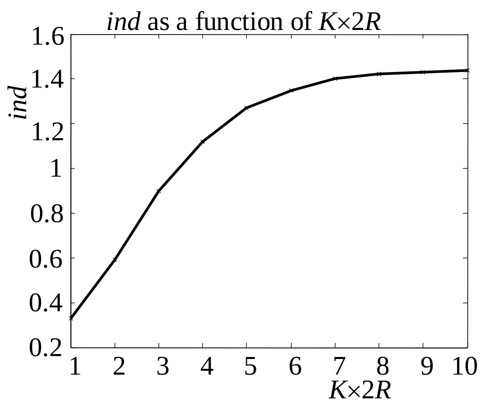

Figure 14, *ind* as a function of $K\times2R$

The following adaptation rule was used for the gain

K. Note that the desired value of $K \times 2R$ is 5.

$$\frac{dK}{dt} = \begin{cases} 0.1 & \text{, if } ind \le 1.1 \times 10^{-4} \\ -10 & \text{, if } ind > 1.1 \times 10^{-4} \end{cases} \quad (4)$$

A number of simulations were done using various value of *R* when the reference signal is a pulse train with amplitude of 0.005 (m) and frequency of 1 Hz. In Figure 15, it can be easily seen that the adaptation law works as desired and the value of $K \times 2R$ is close to 5 in all of the cases. Figure 16 shows the difference between the response of the PSD signal when the simulation was started (solid line with $K(0) = 3$) and after 60 seconds (dashed line when $K(60) = 1$). The solid line is the desired response with %overshoot at around 30%. The dashed line can also be used to show what might happen if the system is designed with the nominal value $K \times 2R = 5$ but the loop gain is increased by 3 times; e.g., *R* increases 3 times. Large value of *R* can cause more oscillatory and can cause the laser to fall off the retroreflector in actual applications.

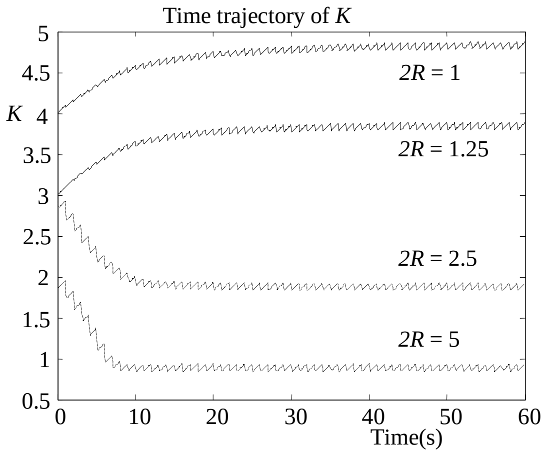

Figure 15, Trajectory *K*(t) with various *R* and *K*(0).

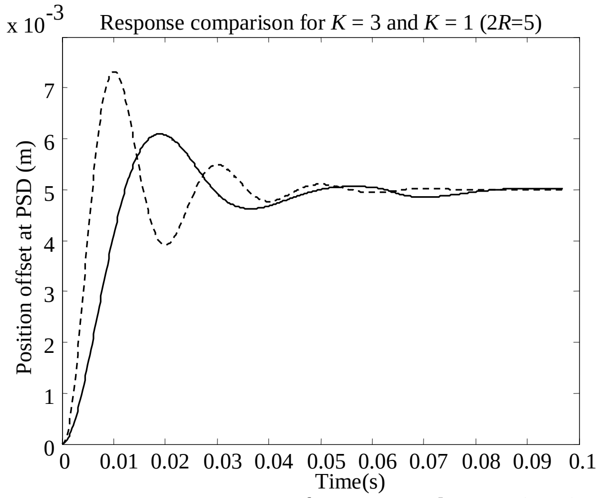

Figure 16, PSD Response for *K* = 3 and *K* = 1 (*R*=5)

5. Conclusion

This paper describes the tracking control issues of the LPS system. Two control laws were studied. Tuning of the controllers on the actual hardware was performed and the two-loop system was found to be superior. One of the problems found was the significant of the distance of the retroreflector from the tracking mirror. To reduce this problem without directly measures this distance, two approaches were proposed. Base on simulation results, the second method of adapting the controller's gain using an indicator of how much the system's loop gain differs from the desired value is more suitable for actual implementations.

Acknowledgments

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