JOURNAL OF AUTOMATIC CONTROL, UNIVERSITY OF BELGRADE; VOL. 13(2):17-22, 2003 ©

Experimental Study on Low Velocity Friction Compensation and Tracking Control

Milos R. Popovic, Guangjun Liu, and Andrew A. Goldenberg

Abstract— **Stick-slip phenomenon is often associated with the control of low velocity motion because of the positional dependancy of friction and negative damping friction that decreases as the motion speed increases. In this paper, smooth low velocity tracking control of a commercial robot joint is demonstrated experimentally using a combination of high gain PID control, fast sampling rate and high position sensor resolution. The experimental results also reveal that the main source of instability is not negative damping friction, but position dependant friction that has been widely neglected. The short sampling period and a high resolution encoder have allowed us to compensate for the position dependant friction with a PID controller with sufficiently high gains.**

Index Terms—**Friction compensation, tracking control, robot control, low velocity friction, experiment.**

I. INTRODUCTION

IN the control of slow motion of mechanical systems, stick-slip phenomenon is often believed to arise from negative damping friction which decreases as the motion speed increases. Numerous attempts were made in the past to develop controllers that can perform low velocity tracking in the presence of negative damping friction. Typical relevant approaches presented in literature are: friction compensation using dither signal [1]; friction compensation through position or force control using high gain feedback [11,14]; adaptive feedback friction compensation [4-7,12]; robust nonlinear friction compensation [2,3,25]; model-based feedforward and feedback friction compensation [15-17,24,28,29]; friction compensation using H_∞ control [26,27]; and friction compensation using fuzzy logic control [8].

Experimental results on friction compensation have also been reported in the past. However, despite sounding stability analysis based on various friction models, the experimental results reported are not satisfactory in the very low velocity region where the negative damping friction exists. Extensive experimentation with dither signals has shown that dither reduces the unwanted effects of negative damping friction but does not eliminate them [1]. The experimental results of a high gain feedback controller proposed in [14] indicate a large positioning error of $\pm 3^\circ$. The experimental results of adaptive control presented in [4,6] show poor tracking performance at very low velocities. The experimental results on robust nonlinear friction control reported in [2,25,30] also show low positioning accuracy. To the best of the authors' knowledge, successful experiments in the velocity region of negative damping friction without stick-slip have not been reported yet. The authors believe that one of the main reasons for the controllers mentioned above not achieving high performance in the velocity region of negative damping friction in the reported experiments is that position dependency of friction is not properly dealt with, which is quite significant in complex mechanisms [1,22,23].

In this paper, smooth low velocity tracking control of a PUMA 560 robot joint despite negative damping friction is demonstrated experimentally using a combination of high gain PID control, fast sampling rate and high position sensor resolution. The experimental results also reveal that the main source of instability is not negative damping friction, but position dependant friction (PDF) that has been widely neglected. The short sampling period and high resolution encoder have allowed us to compensate PDF with a PID controller with sufficiently high gains.

The paper is organized as follows. After a description of the experimental setup in Section 2, the controller design is discussed in Section 3, and the experimental results obtained with the proposed controller are reported in Section 4. Discussion and conclusions are given in Sections 5 and 6, respectively.

II. EXPERIMENTAL SETUP

The experiments described in this paper were performed with the first joint of a PUMA 560 robot [30] (Figures 1 and 2). This mechanical system was used in our experiments for two reasons. The first reason was that the first joint of PUMA 560 robot represents a fairly complex mechanism whose low velocity tracking performance is significantly influenced by the negative damping friction [22]. In Figure 3 an experimentally obtained friction characteristic of this joint is provided for angular positions from -2480 to -2500 encoder increments and for angular velocities from 0 rad/sec to -0.2 rad/sec [22]. The second reason was that Armstrong, who significantly contributed toward better understanding of friction and friction phenomena, performed most of his experiments using the same mechanism [1]. Hence, by conducting the experiments with

---

Manuscript received November 16, 2003. This work was supported in part by MMO, Ontario, Canada.

M. R. Popovic is with the Institute of Biomaterials and Biomedical Engineering, University of Toronto, Fax: +1-416-978-4317, Phone: +1-416-978-6676, (milos.popovic@utoronto.ca)

G. Liu is with the Department of Aerospace Engineering, Ryerson University, FAX: +1-416-979-5056, Phone: +1-416-979-5000, (gjliu@ryerson.ca)

A. A. Goldenberg is with the Robotics and Automation Laboratory, University of Toronto, Fax: +1-416-978-7753, Phone: +1-416-978-5745, (golden@utoronto.ca)

the same hardware we were able to compare our results to already established findings published by Armstrong [1].

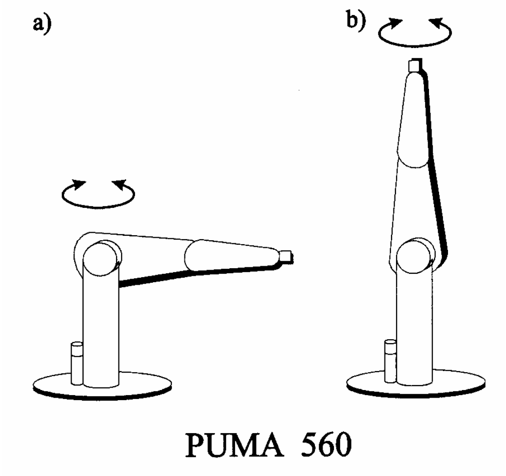

Figure 1: Arm configurations used in experiments

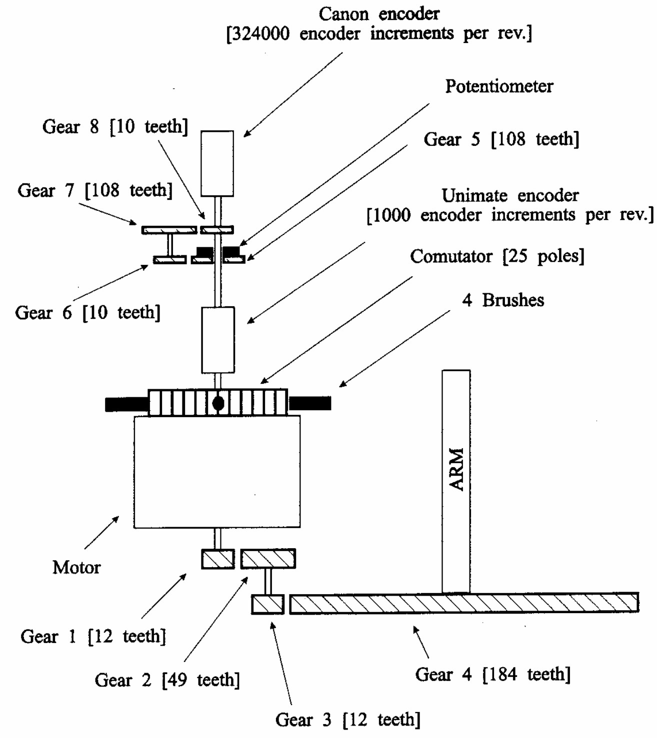

Figure 2: Schematic diagram of the first joint of the PUMA 560 robot

The first joint of PUMA 560 robot is actuated by a permanent magnet DC motor. Position and velocity measurements of the first joint are obtained from two encoders mounted on the motor shaft as shown in Figure 2. The built-in Unimate encoder, whose resolution is 62610 encoder increments per joint revolution [30] (1000 encoder increments per encoder's shaft revolution), is used to measure position. A Canon Laser Rotary encoder, whose resolution is 20285640 encoder increments per joint revolution [21] (324000 encoder increments per encoder's shaft revolution), was added for both position and velocity measurement.

The first joint is controlled with a modified Unimate controller [30] which allows both, open-loop and closed-loop control of the mechanism. In closed-loop control, the original Unimate controller is used. In open-loop control, a part of the Unimate controller which computes the control function is bypassed using a PC based controller. This feature enabled us to carry out experiments with the high gain PID controller and the high-resolution rotary encoder in the feedback loop. The control program was written in C^{++}, and the sampling period was 1.5 ms.

It is important to stress that the high-resolution rotary encoder attached to the first joint's motor shaft enables us to measure friction as a function of position with accuracy 324 times higher than the positional accuracy obtained with the built-in Unimate encoder. For example, this rotary encoder can measure the positional dependency of friction generated by meshing of gears 3 and 4, shown in Figure 2, with an accuracy of $5.498 \times 10^{-8}\, m$ [22]. This positional accuracy is higher, by an order of magnitude, than the accuracy $10^{-7}\, m$ which has been suggested as sufficient for measuring PDF as a smooth function of position [1,10]. In addition, the control program used in the experiments implemented a sampling period of 1.5 ms. The combined use of a short sampling period and a high resolution encoder played a key role in enabling the high gain PID controller (Kp = 122, Kd = 40, and Ki = 17) to perform stable low velocity tracking in the presence of negative damping friction, as discussed in the following sections.

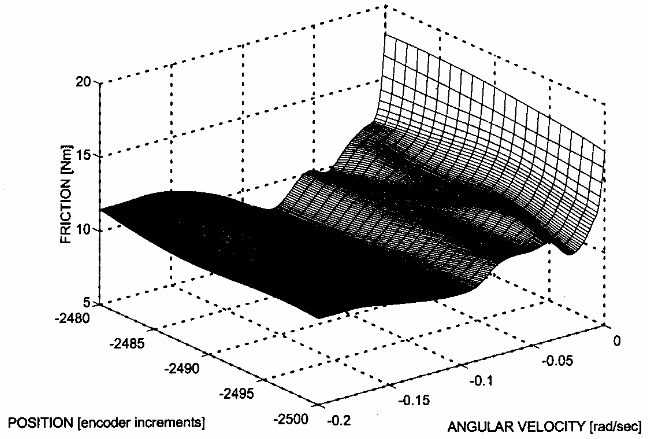

Figure 3: Measured friction characteristics of the first joint of PUMA 560 robot given as a function of position and velocity

III. CONTROLLER FOR LOW VELOCITY TRACKING

A theoretical analysis conducted by Dupont in 1991 [11] indicates that a high gain PID controller should be capable of performing low velocity tracking in the presence of negative damping friction. However, this finding was not demonstrated experimentally, which we believe was due to the existence of additional source of instability. It was suggested in [20,22,23] that PDF is source of this additional instability. The PDF maybe responsible for poor tracking control performance, rather than negative damping friction, which has historically been considered responsible for the poor low velocity tracking of conventional controllers. The main problem with PDF is that when it is measured as a function of position at low velocities, using low or medium resolution position encoder, the obtained measurements suggest that PDF changes instantaneously with position causing fluctuations as high as ±30 % in the overall friction [1,13,22,23]. As a result, the available friction compensators, which commonly use low or medium resolution position encoders to measure the position of the mechanism, are incapable of compensating for such large instantaneous friction fluctuations, causing mechanical systems to suffer from stick-slip effect which generates poor low velocity tracking.

Dahl [9], and Osborn and Rittenhouse [19] published findings which indicated that the establishment and breaking of asperity contacts during the boundary lubrication and partial fluid lubrication regimes (negative damping friction) can be described with a continuous smooth function if this phenomenon is observed with positional accuracy higher than or equal to $10^{-7}\,m$ [1,10]. As the PDF represents a force or torque which is generated by the establishment and breaking of numerous asperity contacts it can be expected that PDF could also be described with a continuous smooth function if its positional dependency is observed with such accuracy. Therefore, if a sufficiently accurate instrument for measuring position is used, PDF could be measured as a smooth continuous function of position, instead of a random function as previously reported. As a result, velocity estimates would also be smooth functions of position (or time) enabling the use of a high gain PID controller to perform stable low velocity tracking despite negative damping friction. It is important to mention that this PID controller requires a very short sampling period in order to enable the positional encoder to measure the positional dependency of friction with the above accuracy.

IV. EXPERIMENTAL RESULTS

The low velocity tracking experiments reported in this paper were conducted as follows. First, the robot arm was positioned at a predetermined starting point. Second, the high gain PID controller was activated and it was set to track a low velocity profile which can be described by the step function shown in Figure 4. The controller was set to track the following constant angular velocities: 0.004, 0.01, 0.05, and 0.1 rad/s. During the experiments, the current, the Unimate encoder and the Canon Laser encoder readings were recorded. In order to compare the performance of the proposed controller with the performance of the existing high gain PID controller the experiments were conducted using a PID controller with both the Canon Laser Rotary encoder and the Unimate Rotary encoder. In both cases the sampling period was 1.5 ms and the gains were tuned up manually to give the best performance (Kp = 122, Kd = 40, and Ki = 17 for both cases when the Unimate and the Canon Laser encoders were applied). As a result, the closed-loop velocity versus position curves were obtained for the above constant angular velocities using both controllers. The experiments were terminated when the robot arm reached a predetermined final position or when the memory used for experimental data storage was filled up. The experiments were conducted for two different arm configurations (see Figure 1) and for two different directions of rotation of the first joint (in total 32 experiments). Due to space limitations, only the experiments performed for the arm configuration shown in Figure 1.b and a clockwise direction of rotation of the first joint are presented.

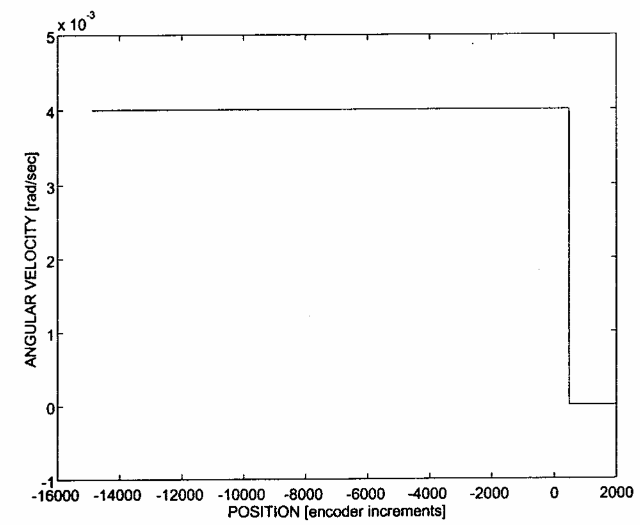

Figure 4: Velocity profile for an angular velocity of 0.004 rad/s

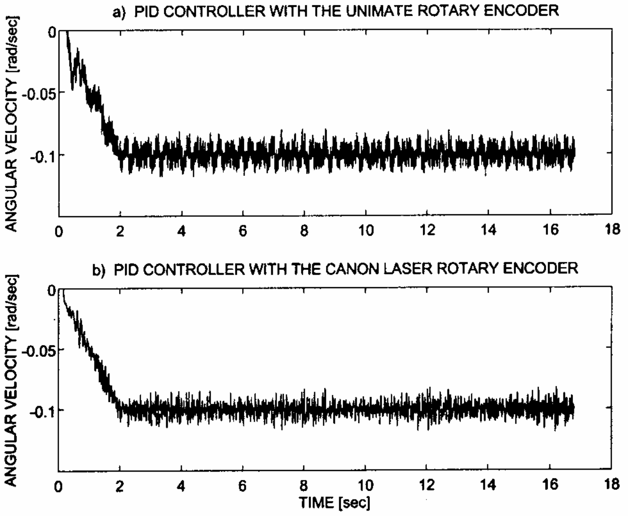

Figure 5: a) The high gain PID controller in closed-loop with the Unimate encoder tracks a constant angular velocity of –0.1 rad/s; b) The high gain PID controller in closed-loop with the Canon laser encoder tracks a constant angular velocity of –0.1 rad/s

The first set of experiments was conducted for an angular velocity of -0.1 rad/s, as shown in Figure 5. The experiment results in Figure 5.a and Figure 5.b were obtained using the high gain PID controller in closed-loop with the Unimate encoder and the high gain PID controller in closed-loop with the Canon Laser encoder, respectively. As shown in Figure 5 both controllers were capable of tracking a constant angular velocity of -0.1 rad/s. This result was expected because an angular velocity of -0.1 rad/s is not in the range of negative damping velocities. As it is within the full fluid lubricated regime, as shown in Figure 3, stable tracking by both controllers was expected.

The second set of experiments was conducted for an angular velocity of -0.05 rad/s, as shown in Figure 6. Contrary to the previous experiment, an angular velocity of -0.05 rad/s is within the range of negative damping velocities, as shown in Figure 3. As a result, the high gain PID controller in closed-loop with the Unimate encoder was unable to perform stable tracking of a constant angular velocity of -0.05 rad/s. The controller was experiencing stick-slip effect as shown in Figure 6.a. On the other hand the high gain PID controller in closed-loop with the high-resolution encoder was capable of performing stable tracking for the same constant angular velocity, as shown in Figure 6.b.

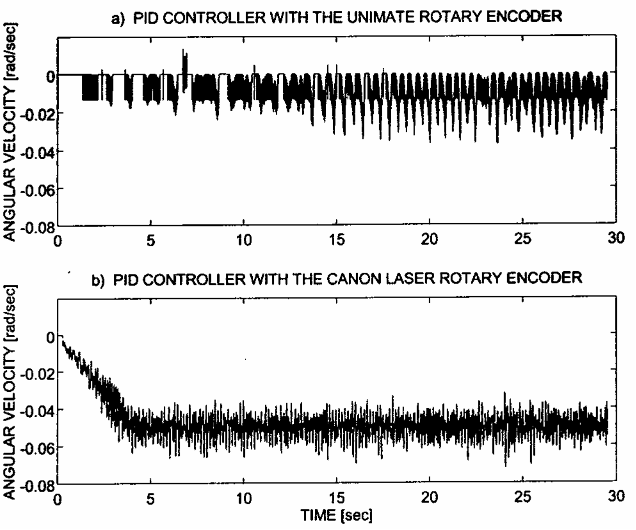

Figure 6: a) The high gain PID controller in closed-loop with the Unimate encoder tracks a constant angular velocity of –0.05 rad/s; b) The high gain PID controller in closed-loop with the Canon laser encoder tracks a constant angular velocity of –0.05 rad/s

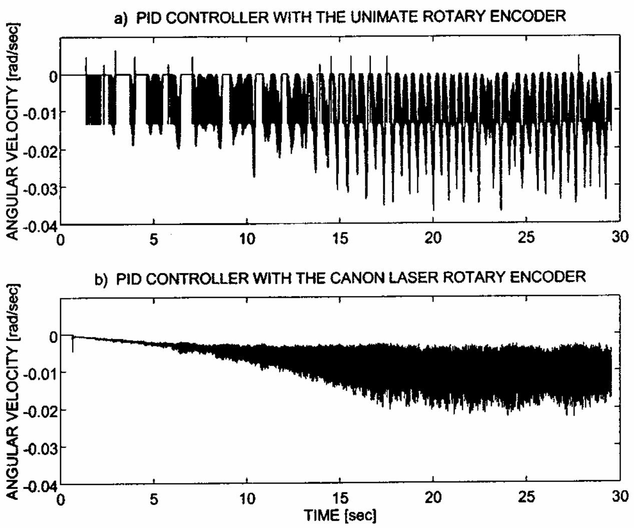

Figure 7: a) The high gain PID controller in closed-loop with the Unimate encoder tracks a constant angular velocity of –0.01 rad/s; b) The high gain PID controller in closed-loop with the Canon laser encoder tracks a constant angular velocity of –0.01 rad/s

The third set of experiments was conducted for an angular velocity of -0.01 rad/s, as shown in Figure 7. Similar to the previous experiment, an angular velocity of -0.01 rad/s is within the range of negative damping velocities, as shown in Figure 3. As a result, the high gain PID controller in closed-loop with the Unimate encoder was again unable to perform stable tracking of a constant angular velocity of -0.01 rad/s. The controller again experienced stick-slip effect as expected (see Figure 7.a). However, the high gain PID controller in closed-loop with the high-resolution encoder was capable of performing stable tracking for the same constant angular velocity, as shown in Figure 7.b. Note that in Figure 7.b the measured angular velocity significantly fluctuates around the desired velocity.

The final set of experiments was conducted for an angular velocity of -0.004 rad/s, as shown in Figure 8. Similar to the previous two experiments, an angular velocity of -0.004 rad/s is within the range of negative damping velocities, as shown in Figure 3. As a result, the high gain PID controller in closed-loop with the Unimate encoder was again unable to perform stable tracking of a constant angular velocity of -0.004 rad/s. As expected, the controller was experiencing stick-slip effect as shown in Figure 8.a. Again the high gain PID controller in closed-loop with the high-resolution encoder was capable of performing stable tracking for the same constant angular velocity, as shown in Figure 8.b.

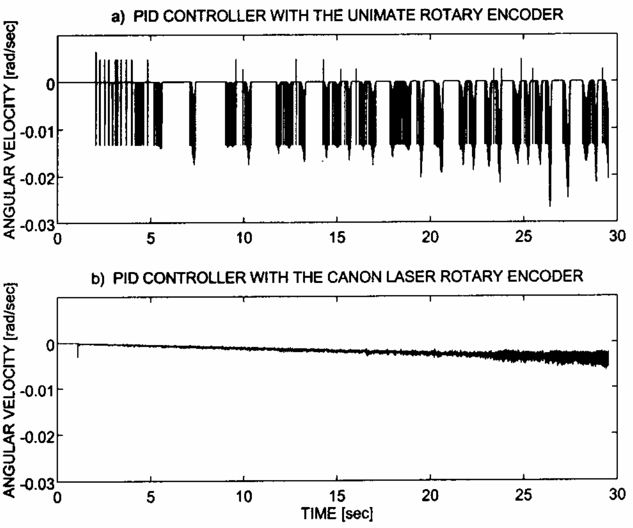

Figure 8: a) The high gain PID controller in closed-loop with the Unimate encoder tracks a constant angular velocity of –0.004 rad/s; b) The high gain PID controller in closed-loop with the Canon laser encoder tracks a constant angular velocity of –0.004 rad/s

Figures 6 - 8 clearly show that the proposed high gain PID controller in closed-loop with the Canon Rotary Laser encoder was capable of performing stable tracking of constant negative damping velocities. To the best of the author's knowledge these are the first successfully conducted low velocity tracking experiments in the velocity region of negative damping friction. The proposed controller was extensively tested for 250 hours in order to find out whether it was stable under all conditions. The test consisted of a series of continuous experiments during which the controller was set to perform low velocity tracking for a variety of different negative damping velocities. In addition, during the test the gains of the PID controller were subject to change. This was done in order to investigate the robustness of the proposed controller. During these 250 hours the controller did not fail to maintain stable low velocity motion.

V. DISCUSSIONS

Although the proposed controller performed low velocity tracking reliably the experiments conducted indicate that the performance of the controller could be further improved. In particular, in the steady state regime the controller tracked the desired velocity with an error, as shown in Figures 7.b and 8.b. A statistical analysis of these errors showed that they have a zero mean value and a relative standard deviation as large as 41 %. The PDF component and measurement errors were most likely the sources of this error.

No.	Source of random friction	Positional accuracy
1	Sliding of brushes and commutator	$0.0355\pi/324000$ $= 3.442\times10^{-7}$ m
2	Meshing of gears 1 & 2	$0.00929\pi/324000$ $= 9.008\times10^{-8}$ m
3	Meshing of gears 3 & 4	$0.355\pi/20285640$ $= 5.498\times10^{-8}$ m
4	Meshing of gears 5 & 6	$0.021\pi/37791360$ $= 1.746\times10^{-9}$ m
5	Meshing of gears 7 & 8	$0.002\pi/324000$ $= 1.939\times10^{-8}$ m

Table 1: Positional accuracies used for measuring positional dependency of PDF components generated by major friction contributors

Before any conclusions can be drawn it must be shown whether or not the high-resolution encoder precision was sufficient to accurately measure the positional dependency of the PDF components generated by all moving parts of the mechanism. As shown in Table 1 the accuracy used to measure the positional dependency of the PDF components generated by major contributors to the overall friction were more than sufficient according to Armstrong's findings [1,10]. Therefore there is another explanation for not obtaining an accurate measure of PDF as expected. The reason for this is a relatively long sampling period. To explain the way in which the sampling time influences the performance of the controller it is assumed that the controller has to track a constant angular velocity of 0.01 rad/s and that the sampling period of the controller is 1.5 ms (which was the sampling period used in these experiments). If this angular velocity is multiplied by the sampling period, an angular displacement of the first joint between two consecutive sampling instances is obtained, which is 0.000015 rad. The equivalent displacement measured on the circumference of gear 4, which corresponds to this angular displacement, is equal to 5.325×10^{-6} m. As the displacement of 5.325×10^{-6} m is larger by an order of magnitude than the precision required to accurately measure positional dependency of PDF generated by gear 4, it can be easily explained why the error caused by PDF was still present in the experiment shown in Figure 7.b. If the desired angular velocity is decreased to 0.004 rad/s and the same sampling period is used, the positional dependency of the PDF generated by gear 4 can be measured with an accuracy of 2.13×10^{-6} m. In other words, by decreasing the desired angular velocity the accuracy used to measure the positional dependency of friction increases causing smaller tracking errors during low velocity tracking experiments.This reasoning concures with experimental results shown in Figures 7.b and 8.b where it is shown that the tracking error decreases by decreasing the desired velocity. From this it can be concluded that the performance of the proposed controller, in particular lowering of the tracking error, could be improved by further reducing the sampling period of the controller. In this particular case the sampling period of 1.5 ms was the shortest that could be implemented with the given personal computer without the risk of failing to meet "hard" real-time constraints. As a result, the performance of the controller could not be further improved without making major changes in the experimental setup which were not possible.

It is also important to notice that the proposed controller comes to steady state after a relatively long transient period. It was found that the settling period differs depending on the angular velocity the controller was given to track. For example, for lower angular velocities the settling period was longer and for larger angular velocities it was shorter. In particular, it was found that the first joint performs approximately the same displacement during the transient period regardless of its duration. For example, in the experiments shown in Figures 5.b - 8.b the mechanism settles in steady state after it performs a displacement which is approximately equal to 0.1 rad.

VI. CONCLUSION

In this paper very low velocity motion control was experimentally demonstrated using a high gain PID controller despite the existence of negative damping friction and position dependant friction. This PID controller has to be implemented with a very short sampling period and a high resolution position encoder to measure the position and velocity of the mechanism. The robustness of the controller was demonstrated by conducting extensive experiments during which the gains of the controller were subject to change and the controller was set to track a variety of negative damping velocities.

The experiments demonstrated that a conventional PID controller proposed by Dupont [11] can perform the low velocity tracking control if the positional dependency of the PDF component is measured with such accuracy that the PDF appears to be a smooth function of position. In this paper in order to measure PDF with this accuracy the Canon Laser Rotary encoder and a sampling period of 1.5 ms were used. It is believed that the performance of the proposed controller could be further improved by shortening the sampling period of the controller and by using a higher resolution position encoder.

REFERENCES

[1] Armstrong-He1ouvry B., Control of Machines with Friction, Kluwer Academic Publishers, Boston, 1991.

[2] Bona B. and Indri M., “Friction Compensation and Robust Hybrid Control,” *Proc. of the IEEE Int. Conf. on Robotics and Automation*, 1993, pp.81-86.

[3] Cai L. and Song G., “A Smooth Robust Nonlinear Controller for Robot Manipulators with Joint Stick-Slip Friction,” *Proc. of the IEEE Int. Conf. on Robotics and Automation*, 1993, pp.449-454.

[4] Canudas de Wit C., Noel P., Aubin A. and Brogliato B., “Adaptive Friction Compensation in Robot Manipulators: Low Velocities,” *The Int. J. of Robotics Research*, Vol.10, No.3**,** June 1991, pp.189-199.

[5] Canudas de Wit C. and Seront V., “Robust Adaptive Friction Compensation,” *Proc. of the IEEE Int. Conf. on Robotics and Automation*, 1990, pp.1383-88.

[6] Canudas de Wit C., “Experimental Results on Adaptive Friction Compensation in Robot Manipulators: Low Velocities,” *Proc. of the 1st Int. Conf. on Experimental Robotics*, 1989, pp.196-214.

[7] Canudas de Wit C., Astrom K.J. and Braun K., “Adaptive Friction Compensation in DC Motor Drives,” *Proc. of the IEEE Int. Conf. on Robotics and Automation*, 1986, pp.1556-61.

[8] Cao C.T., "Fuzzy Compensator for Stick-Slip Friction,” *Mechatronics*, Vol.3, No.6, 1993, pp.783-794.

[9] Dahl P.R., “Measurement of Solid Friction Parameters of Ball Bearings,” *Proc. of 6th Annual Symp. on Incremental Motion, Control System Devices*, 1977, pp.49-60.

[10] Dowson D., “Transition to Boundary Lubrication From Elastohydrodynamic Lubrication,” Boundary Lubrication - *An appraisal of World Literature*, Edited by Ling F.F., Klaus E.E. and Fein R.S. for ASME Research Committee on Lubrication, New York, pp.229-240.

[11] Dupont P.E., “Avoiding Stick-Slip in Position and Force Control Through Feedback,” *Proc. of the IEEE Int. Conf. on Robotics and Automation*, 1991, pp.1470-75.

[12] Friedland B., Mentzelopoulou S. and Park Y.J., “Friction Estimation in Multimass Systems,” *Proc. of the American Control Conference*, Vol.2, 1993, pp.1927-31.

[13] Harnoy A. and Friedland B. “Dynamic Friction Model of Lubricated Surfaces for Precise Motion Control,” *Proc. STLEIASME 1993 Tribology Conf.*, New Orleans, USA, paper No. 93-TC-ID-2.

[14] Gomes S.C.P. and Chretien J.P., “Dynamic Modelling and Friction Compensated Control of a Robot Manipulator Joint,” *Proc. of the IEEE Int. Conf. on Robotics and Automation*, 1992, pp.1429-35.

[15] Johnson C.T. and Lorenz R.D., “Experimental Identification of Friction and Its Compensation in Precise, Position Controlled Mechanisms,” *IEEE Trans. on Industry Applications*, Vol. 28, No. 6, November/December 1992, pp.1392-98.

[16] Kubo T., Anwar G. and Tomizuka M., “Application of Nonlinear Friction Compensator to Robot Arm Control,” *Proc. of the IEEE Int. Conf. on Robotics and Automation*, 1986, pp.722-727.

[17] Leahy M.B. and Saradis G.N., “Compensation of Unmodeled PUMA Manipulator Dynamics,” *Proc. of the IEEE Int. Conf. on Robotics and Automation*, 1987, pp.151-156.

[18] Liu G. and Goldenberg A.A., “Experiments on Robust Control of Robot Manipulators,” *Proc. of the IEEE Int. Conf. on Robotics and Automation*, 1992, pp.1935-40.

[19] Osborn N.A. and Rittenhouse D.L., “The Modeling of Friction and its Affects on Fine Pointing Control,” *Proc. of the AIAA Mechanics and Control of Flight Conference*, 1974, paper No.74-875, pp.1-10.

[20] Popovic M.R., Goldenberg A.A., Shimoga K.B., and Hui R.C., “Model-based Compensation of Friction in Direct-Drive Robotic Arms,” *Journal of Studies in Informatics and Control*, Vol. 3, pp. 75-88, 1994.

[21] Popovic M.R., Gorinevsky D.M. and Goldenberg A.A., “High Precision Positioning of a Mechanism with Nonlinear Friction Using a Fuzzy Logic Pulse Controller,” *IEEE Transactions on Control Systems Technology*, vol. 8, No. 1, pp. 151-158, 2000.

[22] Popovic M.R., Friction Modeling and Control, PhD Dissertation, University of Toronto, Canada, 1996.

[23] Popovic M.R. and Goldenberg A.A., “Modeling of Friction Using Spectral Analysis,” *The IEEE Transactz'ons on Robotics and Automation*, Vol. 14, No. 1, pp. 114-122, 1998.

[24] Schiifer U. and Brandenburg G., “Model Reference Position Control of an Elastic Two-Mass System with Compensation of Coulomb Friction,” *Proc. of the American Control Conference*, Vol. 2, 1993, pp.1937-41.

[25] Southward S.C., Radcliffe C.J. and MacCluer C.R., “Robust Nonlinear Stick-Slip Friction Compensation,” *ASME Winter Annual Meeting*, 1990, ASME paper No. 90-WM/DAC-8, 7 pages.

[26] Takahashi Y. and Hayase M., “Modelling and Design of H. Control for Precise Positioning Control,” *Proc. of the 32nd SICE Annual Conference*, 1993, pp.1373-77.

[27] Takahashi Y. and Hayase M., “Comparative Study of PID and H_∞ Control for Precise Positioning Control,” *Proc. of the 32nd SICE Annual Conference*, 1993, pp.1379-84.

[28] Tung E.D., Urushisaki Y. and Tomizuka M., “Low Velocity Friction Compensation for Machine Tool Feed Drives,” *Proc. of the American Control Conference*, Vol. 2, 1993, pp.1932-36.

[29] Tung E.D., Anwar G. and Tomizuka M., “Low Velocity Friction Compensation and Feedforward Solution Based on Repetitive Control,” *J. of Dynamic Systems, Measurement, and Control*, Vol. 115, June 1993, pp.279-284.

[30] Unimate PUMA Robot Manual 398H, Unimation Robotics, A Condec Company, Connecticut, USA, 1980.