Force Signal Tuning for a Surgical Robotic Arm Using PID Controller

Gamal I. Selim, Noha H. El- Amary, and Dina M. Aboul Dahab

***Abstract*—In this paper, the modeling, control and simulation of a robotic arm is presented. The goal of the controller is to improve and adjust the output force of the arm using Proportional Integral Differential (PID) controllers. Lately the application of robotics in the field of surgery has opened fields of research that has helped ensure the accuracy, durability, dexterity and the ability for repetition. The combination of the human surgeon's judgmental capabilities with these aforementioned characteristics proves to be an interestingly challenging duo/encounter. The studied system is simulated to consist of the equations of the dynamic motion of the robotic arm with the controller participation. Using the concept of force balance between the surgical robotic arm and the organ, PID controllers are added to smoothen and to slow down the output impact force of the robot in all dimensions. The system is investigated without any control system, with PI controller and PID controller. Different gain values for PID controllers are studied. Output obtained from the simulation show satisfactory response.**

***Index Terms*—Surgical robotic arm, force balance concept, force signal tuning, PID controller effect.**

I. INTRODUCTION

Robotics surgery begins to lead the way in the surgical profession with the emerge of advanced and more helpful technology. Surgical robotic devices are classified into: (1) large, high precision robots (image guided or tele-operated), (2) handheld smart medical tools and (3) miniature endoscopic robots. Minimally Invasive Surgery (MIS) is an operation technique established in the 1980s. It differs from open surgery in that the surgeon works with long instruments through small incisions (typically < 10mm) and that he has no direct access to the operation field as in open surgery. It's mentioned that robotic surgery is preferred in MIS for its dexterity, precision and repeatability. For tele-operated robots, it focuses on two examples: the "Da Vinici Surgical System" and the "Zeus" dexterous tele-operated system. An intelligent hand-held instrument and the mechatronic arthroscope for the medical tools are used. Two examples for the endoscopic robots are given namely, the inchworm colonoscopy prototype and the miniaturized system [1]. Three basic disadvantages for the MIS include: (1) due to the indirect surgeon's access to the operating field, the tissues cannot be palpated anymore, (2) the appearing contact force between instrument and tissue can hardly be sensed and (3) direct hand-eye coordinate is lost as the instrument has to be moved around an invariant fulcrum point intuitive using only four degrees of freedom (DOFs) whilst remaining inside the body of the patient due to the kinematic restrictions. Therefore, the surgeon cannot reach any point in the work space at an arbitrary orientation [2]. A tele-operator that supports manipulators in 4 DOFs in the patient and provides visual and haptic sensor is classified in [3]. Reference [4] explains the effect of varying degrees of freedom of force feedback on the performance of manipulation task using a tele-operation system. An experimental evaluation of the role of force feedback in blunt dissection (one of the surgical manipulation tasks employed in minimally invasive surgery) has been carried out [5], [6]. A central scheme for augmented co-manipulation with force feedback is presented where a second force sensor has been found necessary to distinguish manipulator and environmental forces in addition to modifying torques [7].The development of actuated and sensorized instruments for minimally invasive robotic surgery which are a necessary prerequisite for haptic feedback is developed[8]. In reference [9] a 5mm diameter triaxial force sensor has been developed for MIS which measures three force components. The design, implementation and testing for a miniature force sensor developed to measure forces in three dimensions at the tip of a microsurgical instrument is tackled[10]. Reference [11] proposes a model–based controller to correct the command motions where the thin instruments flexion introduces errors into models of the robot kinematics.

Proportional Integral Differential (PID) controller constitutes the most widely used type of feedback. A percentage of more than 90% of the controllers used in the process industries are PID controllers and advanced versions of the PID as proven by an investigation carried out in Japan in 1989. The proportional control action is based on the current value of the control error while the integral control action is based on the past values of the control error. On the other hand, the differential control action is based on the predicted future values of the control error [12].In this paper, a control system is developed to adjust the output reached force of the robotic arm.

II. DYNAMIC MODEL OF A ROBOTIC ARM

A Robotic arm which is used in surgical operation is shown in fig. (1), (2). It consists of two links, a static link and a dynamic link. The junction between the two links has three degrees of freedom represented in the variable of motions q_1, q_2, and q_3.

Manuscript received February 17, 2012; revised March 30, 2012.

Authors are with the Department of Computer Engineering, Arab Academy for Science and Technology and Maritime Transportation, Cairo, Egypt (email: dgamalselim@aast.edu, noha_helamary@hotmail.com, dina_aboul_dahab@hotmail.com).

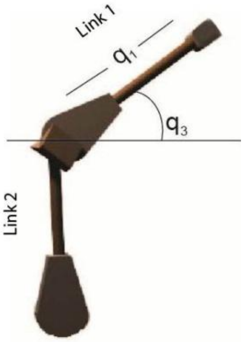

Fig. 1. A side view of the robotic arm

The mathematical model of the dynamic link of the robotic arm is given by the following equations using Lagrange equation [13].

$$\ddot{q}_1 = \frac{1}{m}(u_1 \cos q_3{}^2 + (u_2 - m\dot{q}_1\dot{q}_3)\cos q_3 \sin q_3 - \dot{q}_2\dot{q}_3 \sin q_3^2) \tag{1}$$

$$\ddot{q}_2 = \frac{1}{m}(u_2 \sin q_3{}^2 + (u_1 + m\dot{q}_2\dot{q}_3)\cos q_3 \sin q_3 + \dot{q}_1\dot{q}_3 \cos q_3^2) \tag{2}$$

$$\ddot{q}_3 = \frac{u_3}{I} \tag{3}$$

where;

q_1 denotes the elongation of the arm, q_2 denotes the heading direction, q_3 denotes angle with q_2 plane ($0<q_3<\pi/2$), M is the mass of the robotic arm, I is the robotic arm inertia about the axis of rotation, (u_1,u_2) are the forces along the (q_1,q_2) directions and u_3 is the torque about an axis through the contact point and orthognal to the plane.These equations are derived from lagrange equation to get:

$$u_1 = m\ddot{q}_1 - \lambda \sin q_3 \tag{4}$$

$$u_2 = m\ddot{q}_2 + \lambda \cos q_3 \tag{5}$$

$$u_3 = I\ddot{q}_3 \tag{6}$$

where;

λ is the lagrange multiplier, by applying the velocity constraint

$$\dot{q}_1 \sin q_3 - \dot{q}_2 \cos q_3 = 0 \tag{7}$$

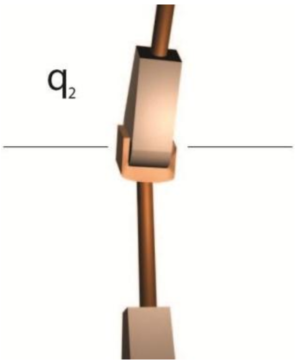

Fig. 2. A front view for the robotic arm

Differentiating this constraint, we get

$$\overset{\grave{e}}{q}_1 \sin q_3 + \dot{q}_1\dot{q}_3 \cos q_3 - q_2 \cos q_3 + \dot{q}_2\dot{q}_3 \sin q_3 = 0 \tag{8}$$

Solving equation (6) and (8), we get

$$\lambda = (u_2 - m\dot{q}_1\dot{q}_3)\cos q_3 - (u_1 + m\dot{q}_2\dot{q}_3)\sin q_3 \tag{9}$$

III. CONTROL SCHEME

A developed control system is designed to control the output force signal of the robotic arm. The control system depends on the force balance concept between the organ and the robotic arm. The system response is evaluated before and after inserting the controller. The controller design is evaluated using a PI and a PID controller and the results are investigated. A general representation for the whole system of the robotic arm with its controller is shown in fig.3. A part of the simulated system on the simulink is clarified in fig. 4. The input per unit predetermined force signal from the organ (reference signal) and the output feedback signal of the forces are marked in fig. 4.

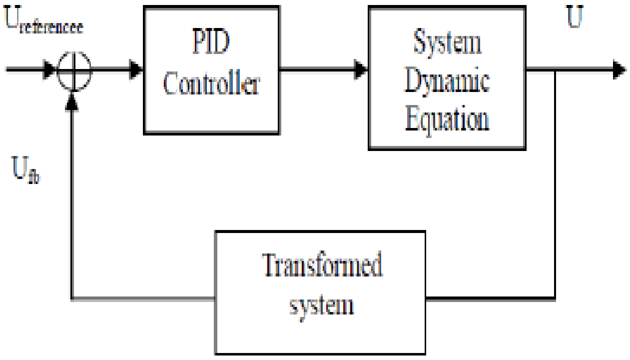

Fig. 3. System representation for the whole system of the robotic arm

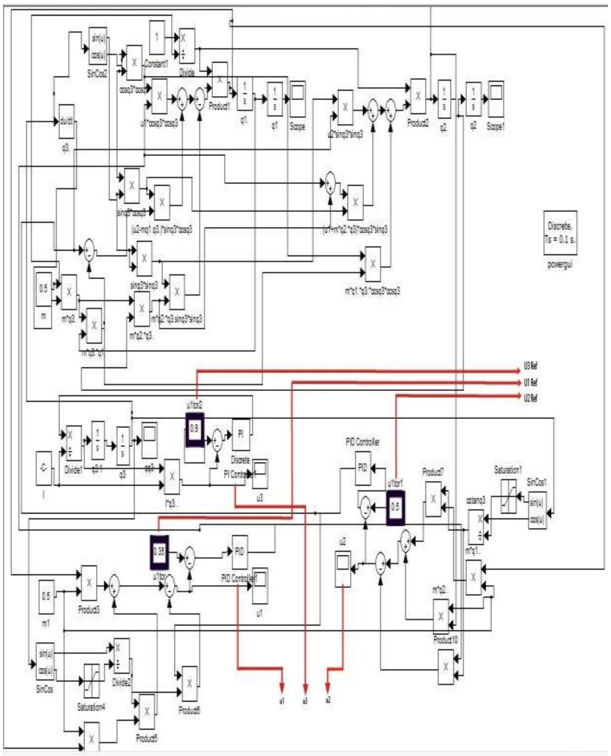

Fig. 4. A part of the simulink for the simulated robotic arm

IV. TUNED FORCE SIGNAL RESULTS

After simulating the studied system on the simulink, the output force results of the system is clarified as follows. The responses of the output force u_1 are shown in fig. 5, fig. 6, fig. 7, fig. 8. All the diagrams show the variation of the output force from the robotic with time. Fig.5 represents the response of the system without any controller. The output force for the organ with time isn't reached. Some oscillations appeared after t=65seconds that became greater with time without halting (unstable case).

When PI controller is used as shown in fig. 6, the output force reaches the required reference signal but with an unacceptable oscillatory behavior as in the case before. An observable improvement (as illustrated in fig. 7) appears when a PID controller is applied though with some oscillations and a 10% maximum overshoot which is however unacceptable for a surgical robot. When the proportional gain is adjusted, the robotic arm reaches a smooth output force signal as shown in fig.8. The output force u_2 is shown in fig. 9, fig. 10, fig. 11, fig. 12. A trial is carried out in the beginning without a controller which results in a quick exponential rising of u_2 with time as shown in fig.9. A noted overshoot occurs when a PI controller is applied which is unacceptable in robotic surgery as in fig. 10. By applying the PID controller, the output force reaches the required reference signal, but with the unacceptable oscillatory behavior as in the previous case (as illustrated in fig. 11). With some tuning applied, fig. 12 clarifies an acceptable smooth response for the output force. Fig. 13, fig. 14 represents the output force response u_3 in the absence of any controllers and in the presence of a PI controller respectively. A result below the required was noticed in the former and more acceptable one in latter.

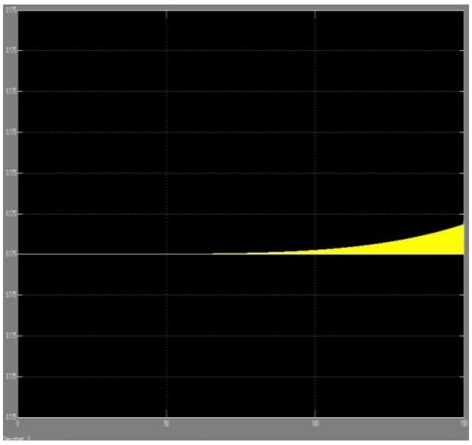

Fig. 5. The force u_1 versus time without applying PID controller

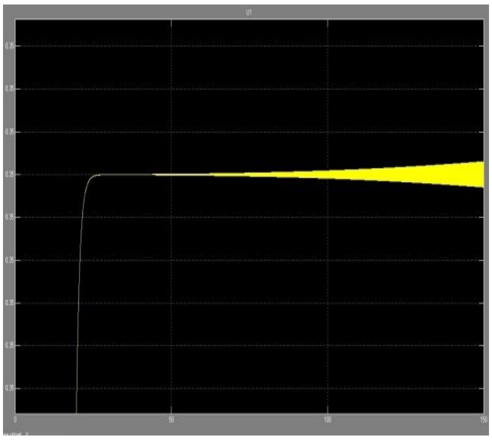

Fig. 6. The force u_1 versus time after applying PI controller (K_p= 0.1, K_i= 1)

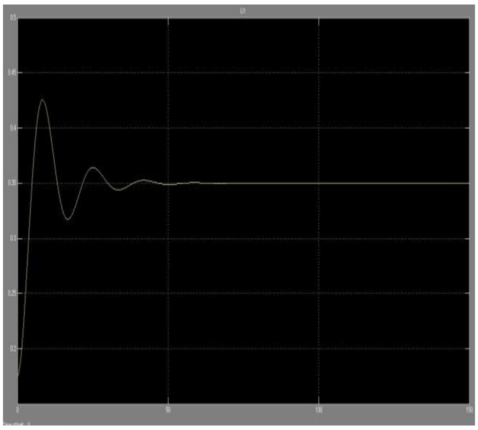

Fig. 7. The force u_1 versus time after applying PID controller (K_p= 1, K_i=1.5, K_d= 10)

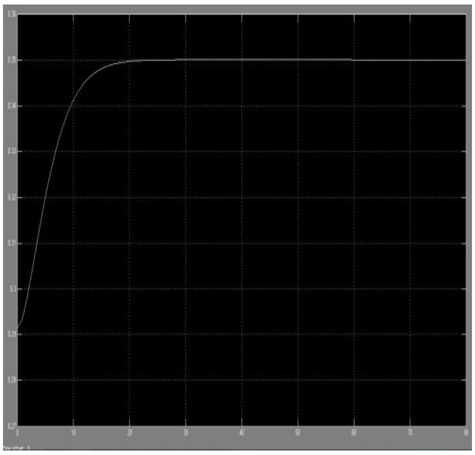

Fig. 8. The force u_1 versus time after applying PID controller (K_p= 5, K_i= 1, K_d= 10)

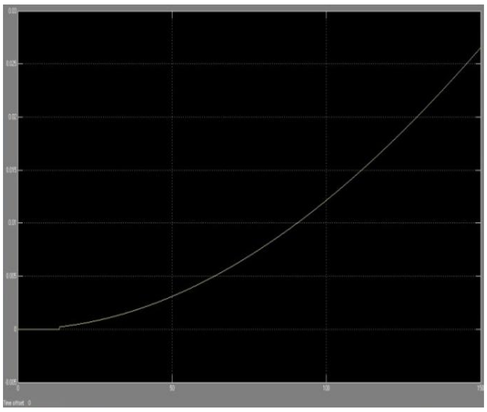

Fig. 9. The force u_2 versus time without applying PID controller

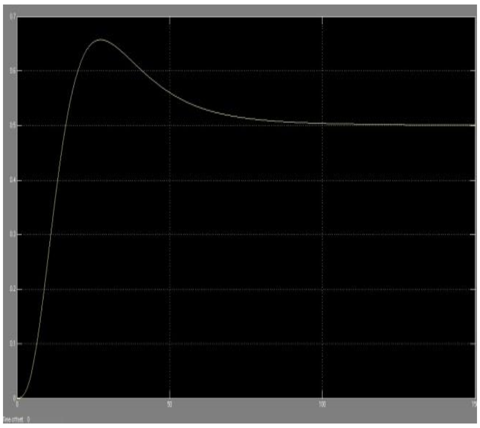

Fig. 10. The force u_2 versus time after applying PI controller (K_p= 1000, k_i= 100)

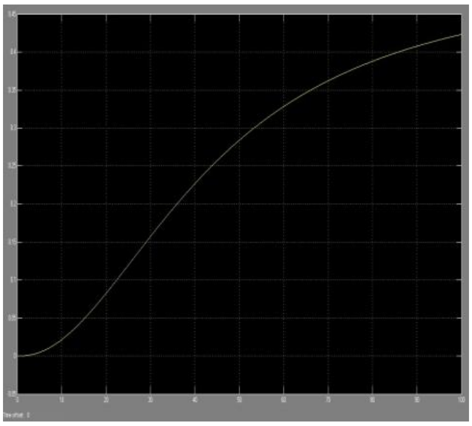

Fig. 11. The force u_2 versus time after applying PID controller (K_p= 120, K_i = 0.01, K_d = 1)

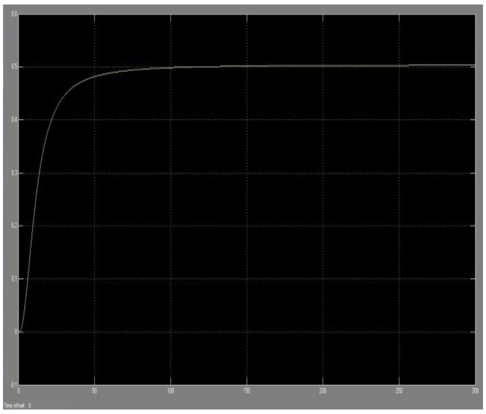

Fig. 12. The force u_2 versus time after applying PID controller (K_p = 2000, K_i = 1,K_d = 1000)

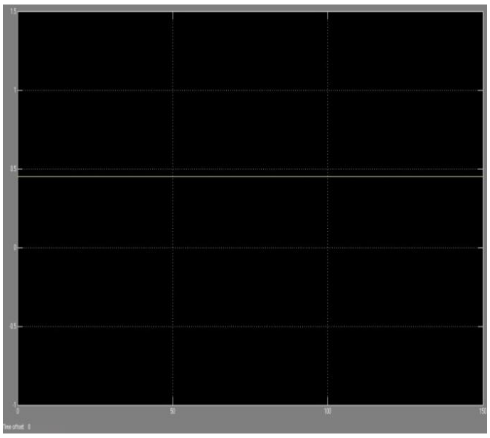

Fig. 13. The force u_3 versus time without applying PI controller

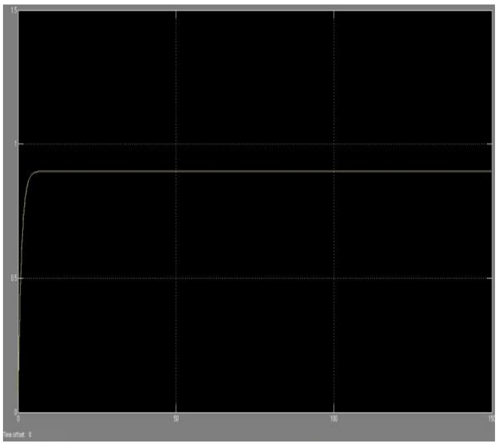

Fig. 14. The force u_3 versus time after applying PI controller (K_p = 0.1, K_i = 1)

V. CONCLUSION

Tuning of output force from a robotic arm which is used in robotic surgery is presented in this paper. The robotic arm dynamic is simulated and investigated at the junction between robot arm links utilizing simulink. The arm consists of two links. The three dimensions forces of the dynamic link are studied. The target is to produce a smooth and relatively slow force reaction from the robotic arm .The system is studied at the beginning in the absence of controllers which resulted in poor results with great oscillation and overshoot in addition to a huge divergence from the expected reference. Three controllers for the three dimension reference forces were added but the results of two dimension forces (u_1, u_2) continued having great oscillation and percentage of overshoot while the third (u_3) converts to the anticipated outcome. With the introduction of PID controller into our study and refining its gain values the results began to convert towards the required results.

REFERENCES

[1] P. Dario, A. Menciassi, and Scuola Superiore Sant' Anna, “Robotics for surgery”, CRIM-ARTS lab, Pisa, Italy, Proceedings of the second joint EMBS/BMES conference Houston, TX,USA October, 2002.J. Clerk Maxwell, A Treatise on Electricity and Magnetism, 3rd ed., vol. 2. Oxford: Clarendon, 1892, pp.68–73.

[2] Barbara Deml1, Tobias Ortmaier2, Ulrich Seibold2, “The Touch and Feel in Minimally Invasive Surgery”, *IEEE International Workshop on Haptic Audio Visual Environments and their Applications*, Ottawa, Ontario, Canada, October 2005.

[3] Tobias Johannes Ortmaier, “Motion Compensation in Minimally Invasive Robotic Surgery”, Ph.D. thesis. *Institute of Robotics and Mechatronics*, German Aerospace Center, 2003.

[4] Wagahta Semere, Masaya Kitagawa, and Allison M. Okamura, “Teleoperation with Sensor/Actuator Asymmetry: Task Performance with Partial Force Feedback”, The symposium on Haptic Interfaces for virtual environment and teleoperator systems, *IEEE virtual Reality*, Chicago, IL, 2004.

[5] Christopher R. Wagner, Nicholas Stylopoulos, and Robert D. Howe, “The Role Of Force Feedback In Surgery: Analysis Of Blunt Dissection”, *Tenth Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, Orlando, March, 2002.

[6] Christopher R. Wagner, Nicholas Stylopoulos, Patrick G. Jackson, and Robert D. Howe, “The Benefit of Force Feedback in Surgery: Examination of Blunt Dissection”, Presence: *Teleoperators and Virtual Environments* (awaiting publication in 2007).

[7] B. Cagneau, G. Morel, D. Bellot, N. Zemiti, and G.A. d’Agostino, “A Passive Force Amplifier”, *IEEE International Conference on Robotics and Automation Pasadena*, CA, USA, pp. 19-23, May, 2008.

[8] Ulrich Seibold, Bernhard Kuebler, Holger Weiss, Tobias Ortmaier, and Gerd Hirzinger, “Sensorized and Actuated Instruments for Minimally Invasive Robotic Surgery”. Proceedings of the *EuroHaptics Conference*, 2004.

[9] Jan Peirs, Joeri Clijnen , Dominiek Reynaerts, Hendrik Van Brussel a, Paul Herijgers, Brecht Corteville, and Sarah Boonea, “A micro optical force sensor for force feedback during minimally invasive robotic surgery”, July, 2004.

[10] Peter J. Berkelman, Louis L. Whitcomb, Russell H. Taylor, and Patrick Jensen, “A Miniature Microsurgical Instrument Tip Force Sensor for Enhanced Force Feedback During Robot-Assisted Manipulation”, *IEEE transactions on robotics and Automation*, Vol. 19.

[11] Ryan A. Beasley Robert D. Howe, “Model-Based Error Correction for Flexible Robotic Surgical Instruments”. *Robotics: Science and Systems* pp. 359-364 , 2005.

[12] Antonio Visioli, “practical PID controller”, Springer, London (UK), 2006.

[13] Howie Choset, Kevin M. Lynch, Seth Hutchinson, George A. Kantor, Wolfram Burgard, Lydia E. Kavraki, and Sebastian Thrun, Principles of robot motion : theory, algorithms, and implementation, MIT press, Cambridge, MA, June, 2005.

Gamal I. Selim received his B.Sc. from Military Technical College (M.T.C), Cairo, Egypt in 1978. He was working as a teaching assistant from 1978 to

1980 at M.T.C. He got his M.Sc. and Ph.D. from Ohio State University, USA in 1982 and 1985 respectively.

He was a staff member at M.T.C since 1985 till 1999. He joined the Arab academy for Science and Technology, College of engineering since 2000 till now. He is currently the head of Computer Engineering Department. His research interest include digital system design, microprocessor and microcontroller based system

.

Dina M. Aboul Dahab received the bachelor's degree in computer engineering from the Arab Academy for Science and Technology and Maritime Transportation, Cairo, Egypt in 2007. She is currently a teaching assistant of computer engineering in the Arab Academy for Science and Technology and Maritime Transportation. Her currently research interest include surgical robotics, controlled systems and image guided surgery.

Noha H. El-Amary was born in Cairo, Egypt, on September 21, 1978. She received B.Sc. and M.Sc. degrees in electrical engineering from Ain Shams University, Cairo, Egypt in 2000 and 2004 respectively. She received her PhD from Ain Shams University in electrical engineering from Ain Shams University, Cairo, Egypt in 2009. She worked as an associate lecturer from 2004 to 2009 in AAST, Cairo branch, Egypt. She is currently an assistant professor in AAST since April 2009. Her special fields of interest include power system stability analysis, measurement and control

.