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# Control Formulation of a Highly Complex Wire-Driven Mechanism in A Surgical Robot Based on an Extensive Assessment of Surgical Tool-Tip Position/Orientation Using Optical Tracking System

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*Abstract*— **This paper presents a performance assessment of a highly complex wire-driven mechanical system in a surgical robot, MU-LapaRobot. The MU-LapaRobot is a collaborative surgical robot, developed for ongoing robotic research for laparoscopic surgical application. The MU-LapaRobot consists of 1-DOF passive joint for vertical motion, 2-DOF passive boom for planar motions and 4-DOF active surgical tool-holder using parallel mechanism to create a remote center of motion (RCM). The actuating system is located at the robot base, to avoid a motor weight problem for the system, which requires a wire-driven transmitting system to relay the actuating power to the active joints. The developed wire-driven transmitting system is a very complex mechanical system, which generates uncertain behaviors in surgical tool-tip positioning control.**

**This study is to extensively assess the control behaviors of the MU-LapaRobot system for the design of its control formulation to compensate the control uncertainty. The study begins with an investigation under the direct control procedures using a motor controlling system, Maxon EPOS 24/5 positioning controller. The study employs an optical tracking system, NDI Polaris Vicra, to track and collect positions and orientations of the surgical tool-tip in assessment procedure. After gathering the results from the extensive assessment, a control formulation, to compensate for the control uncertainty, has been developed. The results of implementation on the new control formulation have shown decent responses on surgical tool-tip positioning control in MU-LapaRobot.**

## I. INTRODUCTION

MINIMALLY invasive surgery (MIS) is a surgery technique that utilizes small incision with high success for the patient. The general surgeries have an acceptable and widely used procedure that is called laparoscopic surgery, a new choice in modern surgery. Its principle technique consists of piercing through the abdominal wall to form small incisions that reach into the abdominal cavity. These incisions are used for the incision of laparoscopic instruments and an endoscope. However, the surgeon needs to increase the workspace by blowing carbon dioxide gas into the abdomen before he or she starts an operation. With this technique, surgeons do not need to form a large incision and therefore reduce the risk from a large wound.

A laparoscopic technique has more advantages than an open surgery [1, 2]. It can decrease the postoperative pain and recovery time that affects the length of the hospital stay. During the operation [3], it can reduce blood loss and infection rate [4]. Moreover, it improves cosmetics with smaller scars after the operation. However, this technique requires a longer operating time which loss of perception in some surgeons; such as a touching sense and hand-eye coordination changing because the surgeon views a 2-dimension display monitor and the direction of the tooltip motion reverses from side to side movement. Also, it requires more time to climb the learning curve [6].

Our research group has been developing a surgical robot; the MU-LapaRobot [5], for laparoscopic surgical application, a cooperative robot, the robot can work with the user by holding instruments as shown in the figure below. The robot can assist surgeons by holding the laparoscopic instruments or controlling them in an operation.

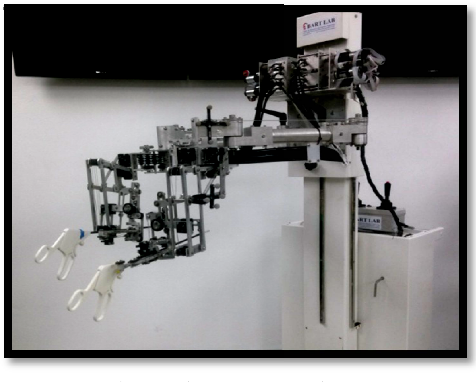

Fig. 1. The MU-LapaRobot

The MU-LapaRobot can fix the instruments in certain position with its electromagnetic brake. So, the robot operates as an assistant by holding instruments in certain positions. Its manipulator consists of 1-DOF passive joint for vertical motion adjustment, 2-DOF passive boom for planar

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motion adjustment and 4-DOF active surgical tool-holder using parallel mechanism to create a remote center of motion (RCM) [5] that means the robot manipulator has a center of motion far away from the robot. This specification is a necessary function in the laparoscopic robot to prevent any damage from the movement of the robot around the incision area.

The prominent characteristic of the MU-LapaRobot is its compact size and the very lightweight robot manipulator. Because the robot actuators, a motor for control at each joint, are placed at the beginning of the robot arm and transfer mechanical power through wire-driven transmission.

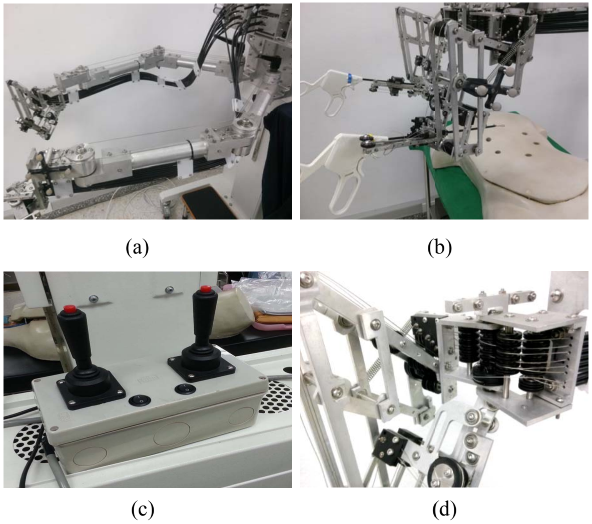


Fig. 2. Complement of MU-LapaRobot, (a) 3 passive DOFs (b) 4 active DOFs (c) a joystick (d) highly complex mechanism with wire-driven transmission

However, the robot control system at the moment is a direct control via joystick. The output response causes unexpected movement. In addition, the MU-LapaRobot will be used for tele-operative purposes in the future [5]. So, the MU-LapaRobot needs improved precision of the tooltip's position and speed control by developing a low-level control. However, the robot has highly complex mechanism and wire-driven transmission which has many sensitive conditions, so the unpredictable motion is a problem that needs to be solved by building the control system of the robot.

## II. INVESTIGATION STAGE

In the first stage, the robot behavior is studied with an assessment procedure and then the data are analyzed for the design of the control algorithm of this robot. After that, the system was integrated to develop position control of the robot manipulator that will be used in the basic control system of the robot. Furthermore, this control system also proves mechanical problems in the robot. The MU-LapaRobot will be developed with the stability for easier control and higher accuracy for an improvement in the future. In brief, we study the controls of the robot in 4 stages.

Stage 1: Investigation and Assessment of Mechanical Errors and Its Behavior.
Stage 2: Control Formulation.
Stage 3: Algorithm and System Integration
Stage 4: Implementation and Algorithm Assessment

The experiments are set as in Fig. 3. The data collection on position and orientation of the robot's end-effector are obtained from observing the robot's behavior by using an optical tracking system, NDI Polaris Vicra® [7]. This system consists of a camera and markers. The tracking camera can track markers which are attached on the manipulator in the assessment as shown in Fig 4. The motor control unit is the part driving the motor of MU-LapaRobot and also controls the direction, speed and position of the robot manipulator. There are 2 controllers, the EPOS2 24/5 Positioning Controller, which are used to control each motor of the robot with high precision and reliability [8].The positioning control, which consists of velocity feed-forward, PID control and feedback from encoder, is used to control the angular position of the robot.

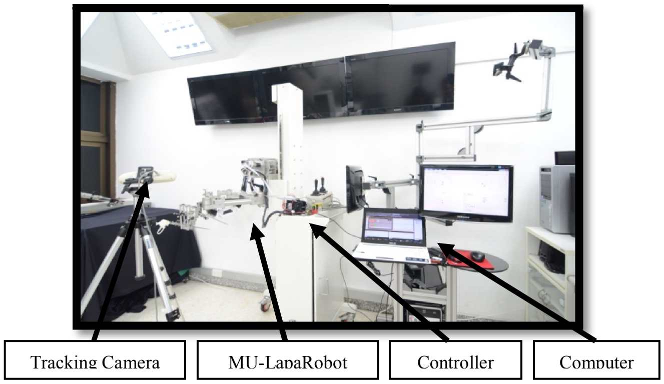


Fig. 3. Assessment setup

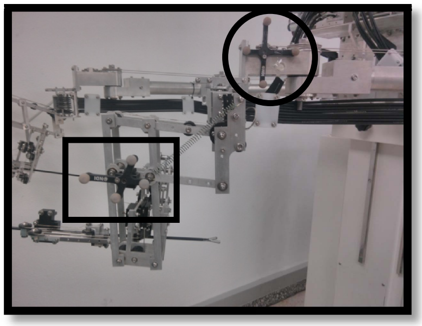


Fig. 4. Marker Attachments: the first piece is at the stationary point (circle), and another one at the tracking point (rectangle)

However, in all of the experiments the velocity motor is stabilized and the target acceleration is set for easier control and assessment because this research observes only the position control. And this paper is also only interested in the 1st and 2nd joint of the robot manipulator that provides a pan motion and tilt motion of a tool movement, because these motions are necessary joints in a cone shape workspace generating the best effect for the position control.

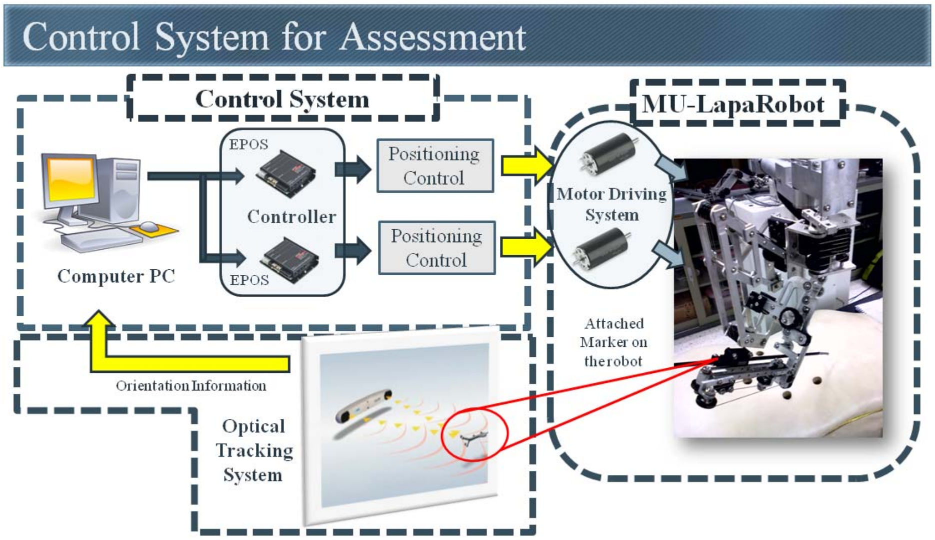


Fig. 5. Overview of control system

## III. THE ROBOT INVESTIGATION AND ASSESSMENT

To study the robot behavior, the robot's accuracy, precision and the corresponding movement of its joints need to be studied first. The investigation topic includes two assessments for easy discussion. The first is an assessment of the accuracy and the corresponding movement and the second is the precision of the robot.

### *A. Accuracy and Corresponding Movement Investigation*

The accuracy investigation aims to study the robot behavior when commanded with varying inputs. In addition, the corresponding movement investigation aims to consider the effects of a joint movement cause the other joint movement. For the first step, the commands are varied from 5° to 45° at 5° interval of pan motion or tilt motion in each direction, and then the data of the pan movement and tilt movement which happen during the experiment are recorded. With this procedure, a set of information for the robot behavior analysis is collected, and they are repeated again for 5 trials to ensure the pattern of behavior as a diagram as shown in the figure below.

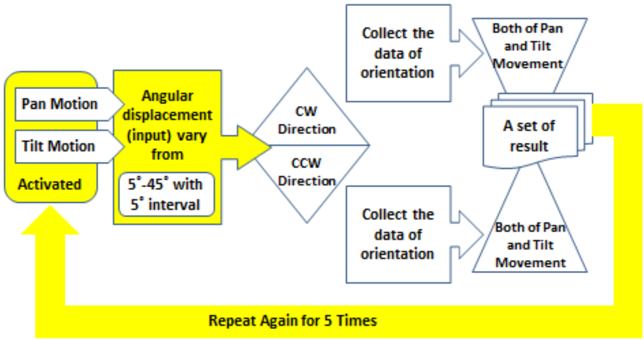


Fig. 6. First assessment diagram: accuracy and corresponding movement investigation

And this is one of the many results from this experiment in the pan motion control. Both of the figures in Fig. 7 are the results at the same time when pan movement is required.

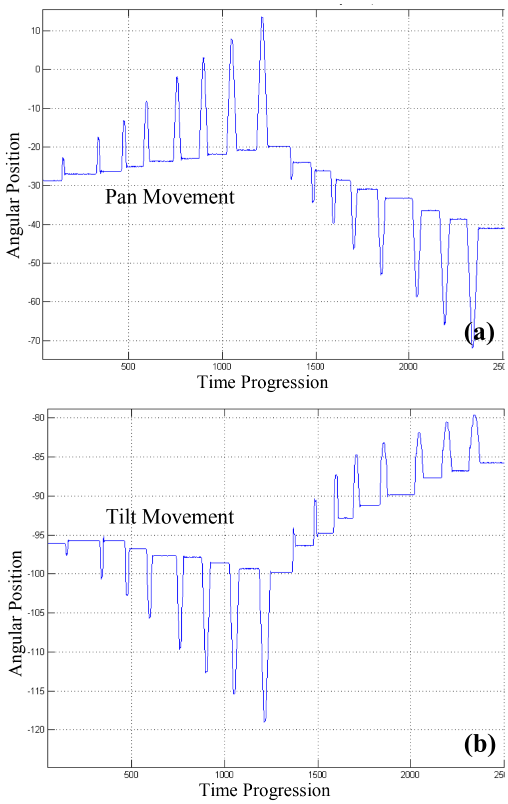
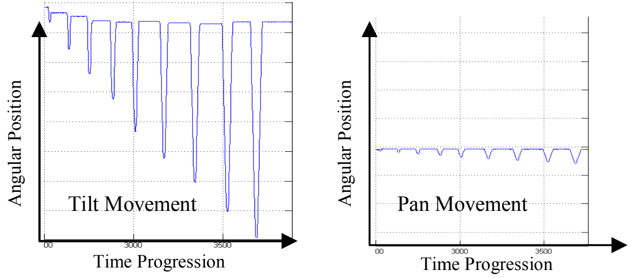


Fig. 7. A result of pan motion assessment, (a) pan movement, (B) tilt movement

There are 3 facts about the robot, which are shown in these figures. The first is the effect of wire tension on loss of required control. It happens in every command and more loss in more angular displacement. The second is the loss of control in the clockwise and counter-clockwise directions which are not equal. That means the result of the same command in different directions is different. And the last fact is the corresponding movement appearance. Fig. 7(b) shows the tilt movement when pan motion is provided.

In addition, the tilt motion assessment shows the same pattern of result as the pan motion assessment, following Fig. 8 (a), but the corresponding effect is lesser than the effect from the pan movement as shown in Fig. 8 (b).



(a) (b)

Fig. 8. A result of tilt motion assessment, (a) tilt movement, (b) pan movement

The robot behaviors in pan motion and tilt motion can be determined from the results in Fig. 9 and Fig. 10 respectively. Therefore in an ideal case, the actual angular displacement should be equal to the command angular displacement that is shown by the black line in the figure, so the behavior curve should be on this line. In each figure we plot 5 behavior curves that show the pattern of each motion. Their standard deviation is 0.0202685 in pan motion and 0.384895 in tilt motion that are acceptable, so this information can be used to design the compensation function in the next stage. This assessment was recorded after changing a wire at the first joint, the pan motion joint, so the pan motion behavior has less error than tilt motion.

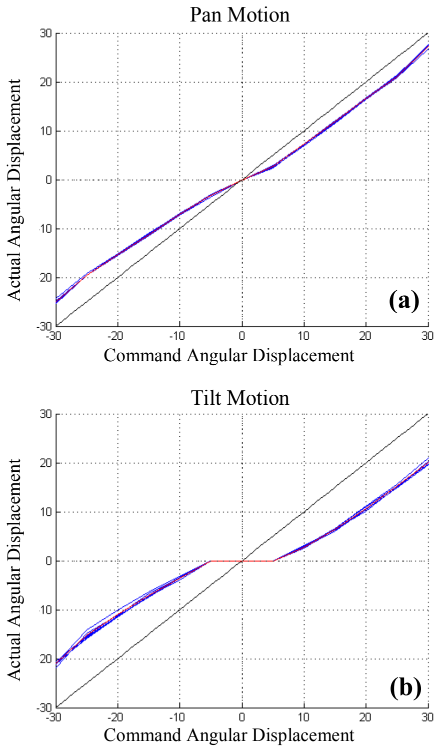


Fig. 9. A result of the robot behavior, (a) pan motion behavior and (b) tilt motion behavior

## B. *Precision Investigation*

Another investigation performed in this study is to measure the precision or repeatability that aims for a study with replicable results. The process is designed to investigate as shown in the figure below. In this experiment, the pan motion orientation and tilt motion orientation is studied again. The inputs are varied from 10° to 45° at 5° increments, but each motion in each variant input is controlled to move direction and counter-clockwise alternately 30 times, and also these processes are repeated 10 times.

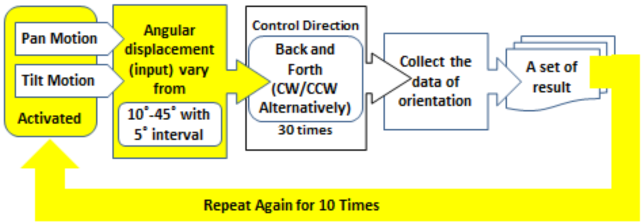


Fig. 10. The second assessment diagram: precision investigation

The repeatability information of the MU-LapaRobot is collected with this experiment. In each variant motion and variant input, the same pattern of results was obtained as is sense in Fig. 11.

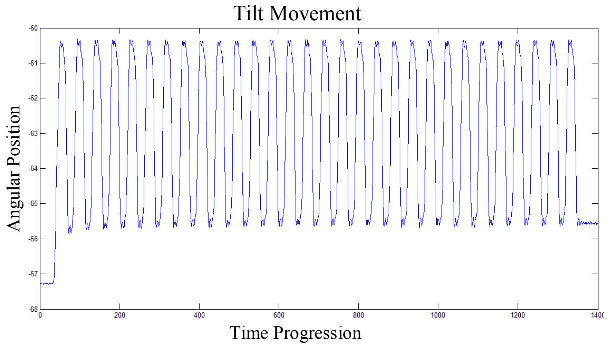


Fig. 11. An example of results of precision experiment: tilt movement with 10° back and forth command 30 times

The figure shows that the robot has high repeatability; the first assessment yielded information about the robot's accuracy, except for the first movement in the experiment. So an addition assumption is expected to explain the shifting in the first time when moving. This phenomenon might happen from some mechanical transmission, which is lost when changing the direction of movement. So an extra experiment was performed by commanding for pan motion in the same direction compared with different direction and a result is collected shown in the figure below. And the expectation is correct, the angular displacement after direction changing is less than the angular displacement from continuous movement, and they occur in both directional inputs, clockwise and counter-clockwise directions.

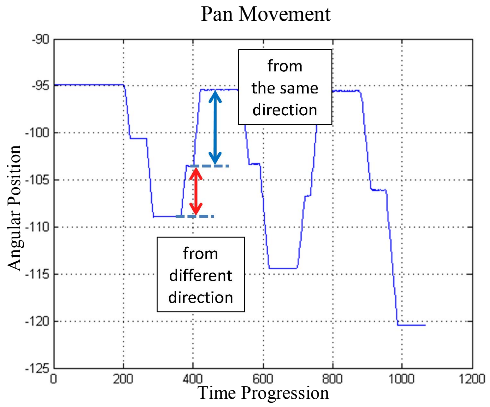


Fig. 12. A extra experiment: the pan movement in the same direction compared with different directions.

## IV. CONTROL FORMULATION

This stage points to the compensatation function design which uses the data from the previous stage. After considering the behavior of the robot, a second order polynomial regression was chosen to fit the behavior of the curve and create a compensated function. These functions are designed under varied conditions following the assessment analysis as listed in the table below:

Table 1. Function in each condition (general case)

| | Continue direction in | Change direction into |
|---|---|---|
| Pan Motion | CW | CW |
| | CCW | CCW |
| Tilt Motion | CW | CW |
| | CCW | CCW |

Moreover, the corresponding movement elimination functions are also needed to compensate other wrong movements. So the corresponding movement compensation in each direction of the pan motion is considered too. The corresponding movement of tilt motion is not designed in this research, because its effect does not disturb the whole system. However, it will be applied to future work. In brief, 10 functions are needed to implement a basic position control of the robot for all conditions.

The equation functions were designed using polynomial regression with second order. So let $\varphi_1$ and $\varphi_2$ be the input values of the pan motion command and tilt motion command, respectively. And $\theta_1$ and $\theta_2$ are the real values of the input that leads to movements to reach the exact goal of the pan motion joint and the tilt motion joint, respectively. They are positive in the clockwise direction and negative value in the counter-clockwise direction. So the general function is

$$\pm\theta_1 = A\varphi_1^2 + B\varphi_1 + C \tag{1}$$

$$\pm\theta_2 = A\varphi_2^2 + B\varphi_2 + C \tag{2}$$

Where the character A, B and C are different constants in each function; their values are listed in table 2. The functions' names in the table are represented with abbreviations. The suffix number represents the motion of the joint, number one means pan motion and number two means tilt motion. The Sign($\pm$) in front of $\theta$ represents the direction of movement, negative means counter-clockwise and positive means clockwise. In addition, the word "cont" means it continues to go in the same direction. On the other hand, the word "chg" means it will change with respect to these directions.

Table 2. Function parameters

| Function | A | B | C |
|---|---|---|---|
| $-\theta_{1\mathrm{cont}}$ | $1.3261 \times 10^{-2}$ | 0.69188 | 2.7492 |
| $+\theta_{1\mathrm{cont}}$ | $9.8785 \times 10^{3}$ | 1.2904 | 0.558668 |
| $-\theta_{1\mathrm{chg}}$ | $-6.5762 \times 10^{3}$ | 1.2269 | 1.6035 |
| $+\theta_{1\mathrm{chg}}$ | $9.5296 \times 10^{3}$ | 1.4279 | $-0.33736$ |
| $-\theta_{2\mathrm{cont}}$ | $3.1239 \times 10^{-2}$ | 0.45359 | 5.028 |
| $+\theta_{2\mathrm{cont}}$ | $-1.6587 \times 10^{-2}$ | 0.65348 | $-4.8758$ |
| $-\theta_{2\mathrm{chg}}$ | $-1.9267 \times 10^{-2}$ | 1.6083 | 5.3028 |
| $+\theta_{2\mathrm{chg}}$ | $1.8036 \times 10^{-2}$ | 1.5789 | $-4.8508$ |
| $-\theta_{2add}$ | $5.2538 \times 10^{-3}$ | $-0.64971$ | 1.7434 |
| $+\theta_{2\mathrm{add}}$ | $-3.8432 \times 10^{-3}$ | $-0.6313$ | $-2.0318$ |

## V. IMPLEMENTATION

In this stage, we integrate all of the functions into the system. We assess the system again with the same process as the investigation in the first stage. The information of pan movement and tilt movement are collected for each condition of each working function.

The figure below shows an example in a condition (general case). The result shows that the robot movements are controlled with high accuracy when applying the function.

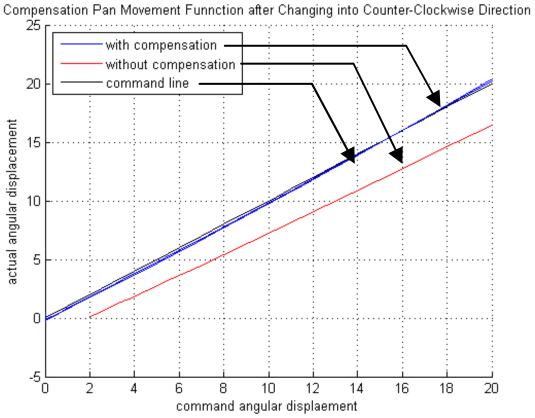


Fig. 13. The result of changing into counter-clockwise of pan motion function assessment

And this is another figure, Fig. 14, which demonstrates the result of the corresponding movement elimination. It works well although it has minor errors, approximately 1 degree, in some parts of movement.

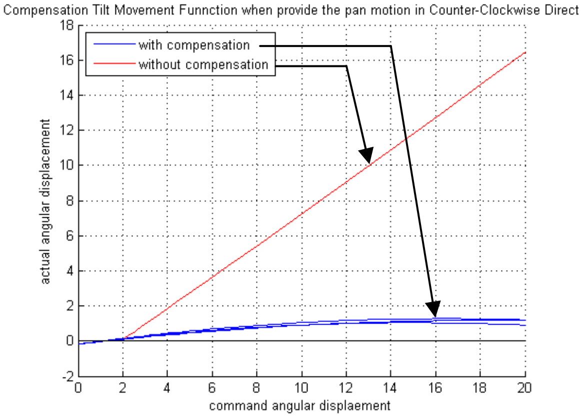


Fig. 14. Tilt movement effect before and after reduction, by the algorithm, in a clockwise direction

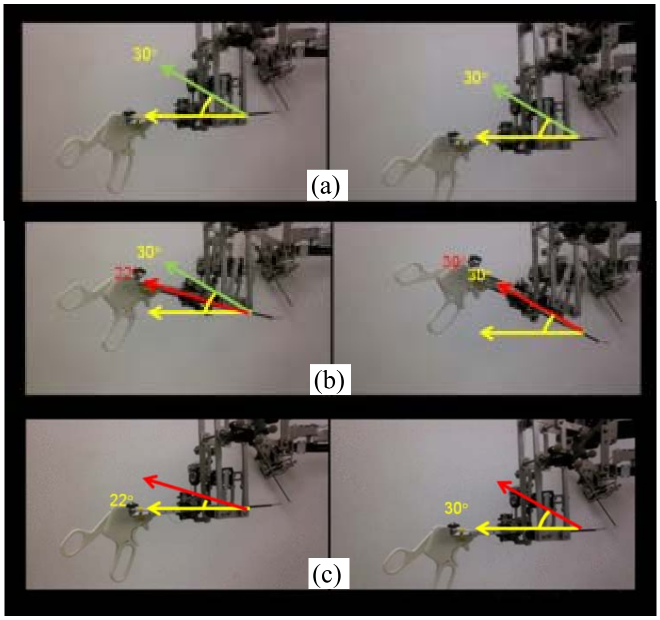


Fig. 15. Movement of tilt motion when command of 30° is inputted with a comparison between original and with function application, left and right respectively, (a) beginning state (b) and (c) the movement result approximately in clockwise direction and counter-clockwise direction respectively

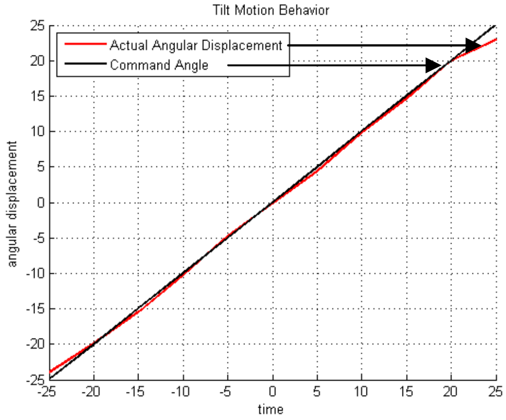


Fig. 16. Tilt motion behavior with compensation

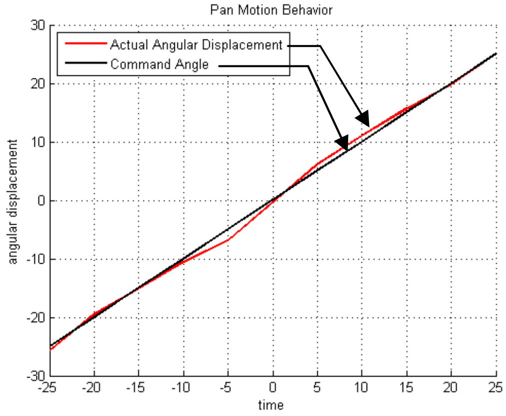


Fig. 17. Pan motion behavior with compensation

## VI. CONCLUSION

The MU-LapaRobot behavior can be predicted and collected to develop a control system with the errors from the robot control investigation. This was done by two part experiment. The first is the wire tension that affects the accuracy of the robot control. The second is the transmission mechanism which causes the corresponding movement and some missing motion. So, we develop a simple feed-forward control system for position control of the tooltip with acceptable accuracy under the same tension condition.

In the future work, we will develop the control system with feedback control for higher accuracy and precision and add some parts that are missing in this research. Moreover, we will also develop and apply speed control for angular velocities handling. Also, a control interface will be added for ease of use.

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