END-POINT POSITION MEASUREMENTS OF LONG-REACH FLEXIBLE MANIPULATORS

KLAUS OBERGFELL and WAYNE J. BOOK

Georgia Institute of Technology, School of Mechanical Engineering, Atlanta, Georgia 30332-0405, USA

Abstract: This paper describes the design, testing and evaluation of a position measurement system for a large flexible manipulator. Previous work is reviewed and updated with a discussion of related sensors and their applicability. Two approaches to accurately measure end-point position over a large workspace are outlined. The chosen approach estimates the tip position from joint angle and link deflection sensors. The equipment used (e.g. sensors, illumination, focusing optics, etc.) and the calibration procedure are presented. Two evaluations of the system are discussed. First static link deflection measurements are compared to results of a static deflection model. Second the combined tip position estimate is compared to an absolute measurement taken with a dial indicator. The paper finishes with a description of expected applications for manipulator control.

Keywords: Flexible Manipulators, Deflection Measurement, Sensing, End-Point Position

1. INTRODUCTION

This paper describes the design, testing and evaluation of a position measurement system for robotics applications. Static tip deflection measurements are compared to results of a static deflection model and to absolute measurements taken with a dial indicator. Precise knowledge of the end-effector position of a manipulator is important for the evaluation of new control routines and as a feedback signal for control. This is especially important when the links of the manipulator are flexible. Many position measurement systems for small laboratory manipulators exist. However, no such system exists for flexible long-reach manipulators. These robotics systems are envisioned to be an integral part of a Department of Energy program to clean up nuclear waste stored in large underground storage tanks. Two testbeds for such systems exist at the Manufacturing Research Center at Georgia Tech. A two-link flexible manipulator denoted as RALF (Robotic Arm Large and Flexible) is considered in this publication. RALF, illustrated in Fig. 1, consists of two 3.05 m long links and operates in a vertical plane.

2. MEASUREMENT METHODS

2.1. Previous Work

Several researchers measured the tip positions of one-link flexible manipulators. These manipulators are typically 1 m long and operate in a horizontal plane. Cannon and Schmitz (1984) used a two-directional lateral-effect photodiode (position sensing photodiode [PSPD]) with focusing lens to detect the x,y-position of a small light bulb mounted at the tip. With the sensor mounted 1 m above the plane of the manipulator, they were able to sense the tip position in a square area with a side of 0.8 m. D. Wang and Vidyasagar (1987) measured the tip deflection with a hub mounted optical system which rotates with the arm. Light from a LED attached to the tip shines onto a mirror mounted at the hub and is reflected onto a linear CCD-array above the hub. The advantage of this system is that the tip deflection can be measured in the whole manipulator workspace. In a similar fashion, W.-J. Wang et al (1989) measured "the slope of arm deflection." A hub mounted one-directional PSPD detects the deflection of a He-Ne laser beam as it shines onto a reflector attached to the flexible arm.

Digital cameras have been used by several researchers for tip position measurements of two-link flexible manipulators operating in a horizontal plane. Oakley and Cannon (1989) and other researchers from Stanford University [e.g. Oakley and Barratt (1990), Ballhaus and Rock (1992)] have used CCD TV-cameras to track a "reflectivity target" at the tip of the arm, where the camera is mounted above the plane of the manipulator. A high resolution CCD permits observation of the whole manipulator workspace. Rattan et al (1990) used a Hamamatsu tracking camera to measure the position of an infrared LED (IR-LED) mounted at the tip of a small two-link flexible arm. The field of view of the camera limited the manipulator workspace to ± 7.6 cm. Lee et al (1990) used a position sensing head camera to measure the end effector position of a two-link flexible arm.

An integrated landmark tracking system (LTS) was used by Nam and Dickerson (1991) for tip position measurements of a one-link flexible arm operating in a vertical plane. The LTS tracks the position of a retroreflective landmark attached to the end-point. Obergfell and Book (1992) used a similar LTS to measure the end-point position of a long-reach two-link flexible manipulator. The achieved resolution of 1-2 mm limited the field of view of the LTS to a subspace (1 m square) of the manipulator workspace. Morikawa et al (1990,1992) used three-dimensional landmarks to yield additional depth information from images. This information is used by the control system of a satellite assembly robot.

2.2. Commercially Available Sensors

Given the task of measuring position within a plane of approximately 10 by 6 meters with an accuracy of 1 millimeter, optical measurements are superior to radio or ultrasound measurements due to the shorter wavelength of light which permits greater accuracy. Such optical sensors for position measurement include cameras (TV, digital), lateral-effect photodiodes (PSPD's), linear CCD-arrays, displacement followers, and laser range finders.

Cameras provide the raw data for digital image processing (DIP) and such tasks as target recognition and scene interpretation. The main disadvantage of cameras is a slow sampling rate. TV cameras are limited to 30 or 60 frames per second (considering US TV standards). The complexity of DIP could decrease this number further unless powerful hardware is used or the image interpretation task is structured, e.g. through the usage of landmarks.

PSPD's are analog sensors with bandwidths of approximately 10 kHz or more. They are available as one or two directional sensors. Their main disadvantage is the need for an active target (e.g. laser, LED, light bulb, etc.). Linear CCD-arrays can be used in a similar fashion but measure only in one axis.

Electro-optical displacement followers are analog sensors based on an image dissector tube. They are capable of tracking a passive target or discontinuity on a moving object with high bandwidths (10 kHz for two directions, 50 kHz for one direction). Their main disadvantage is a relatively high cost (approximately $20,000 for 2 axes).

Laser range finders can provide three-dimensional measurements at high bandwidths. However, the disadvantages of those measurement systems include high price and other complications associated with relatively new technologies (e.g. lack of proven reliability).

Of the four systems outlined, cameras and photodiodes (and linear CCD-arrays) are the most affordable and reliable position measurement systems. Each sensor has its typical advantages, and ideally, they could be used to complement one another. While cameras and DIP should be used for target recognition (e.g. for assembly or placement tasks), PSPD's should be used for low level position and vibration control.

The above mentioned sensors with the exception of laser range finders have similar restrictions of resolution and field of view. Both are ultimately limited by the sensor size as the field of view is fixed for a given sensor size and resolution. Under these restrictions, the given task cannot be accomplished by a single directly measuring sensor. Two distinct approaches alleviate this situation. The first is to extend the field of view of a sensor with a servo-gimbal in such a way that the "sensor window" follows the motion of the arm. The second approach extends the idea of D. Wang and Vidyasagar (1987) to estimate tip position from joint angle and link deflection measurements to more than one link. The second approach is more applicable when the manipulator is moved frequently or when it is not possible to have a measurement system external to the manipulator. The disadvantage of the second method is the indirect measurement. No information can be gained with respect to objects in the environment. We chose to investigate the second approach to measure tip position for low level motion control. If needed a camera or vision system could be attached to the tip to gather data for path planning and higher level controls.

3. EXPERIMENTAL SETUP

Currently, we use two PSPD's to measure the deflection of each link of RALF in its plane of motion. The link deflections are then combined with joint position measurements to yield tip position. The PSPD and a focusing lens are attached to one end of each link and measure the position of a LED at the opposing end of the link. The experimental setup is pictured in Fig.2. The position sensing photodiodes are one-directional sensors with active surface measuring 30 by 4 mm (UDT LSD-30D). They are mounted in a casing with a lens adaptor for 35 mm cameras (Graseby Optronics #1239). The signal from the sensor is processed by an instrumentation amplifier (Graseby Optronics #301-DIV-30kHz).

Sufficient illumination from the light source on the PSPD is necessary for a "noise free" sensor output. The 3.05 m long links of RALF presented some difficulty for finding an appropriate light source. A laser diode provided sufficient illumination over 3.05 m, however the laser beam was too focused and would miss the sensor when the link was deflected. Instead LED's were tested and we found that narrow beam, high power IR-LED's worked best. The LED finally used has 20° half-power points and a spectral rating of 890 nm (Optek 295A, the Siemens SFH 484-2 work also quite well). The peak in the spectral responsivity plot of the sensor is between 900 - 950 nm. The power rating and emitted light energy are largest when the LED's are operated in an intermittent or pulsed mode (designed for remote control). However , the bandwidth of the sensor and instrumentation amplifier (less than 30 kHz) is not large enough to process a very short light pulse from the LED (25 μs max duty cycle). Furthermore, the required "cool-down" period of the LED between pulses would reduce the sampling rate to 500 Hz. Therefore, we decided to operate the LED continuously.

The focusing lens used is a F 5.6 tele-zoom lens set to the maximum focal length of 300 mm. This provides a field of view of 30.5 cm. The signal noise increases at the ends of the range minimizing the usable position measurement range to 20-25 cm. For our application, this is sufficient because a typical tip deflection is approximately 5 cm. Since only 20-25% of the measurement range is used, one could try to use a different lens to focus closer and achieve a better measurement resolution. Unfortunately, none of the tele-photo lenses available could be focussed at a distance of 3 m. Two other possibilities to increase the resolution exist. The first is to use a tele-extender between lens and sensor, which changes the focal length but not the focussing. However, the added optical element decreases the amount of light reaching the sensor surface. The second possibility would be to use a sensor with a shorter active length. An IR passing filter (Schott RG-830 filterglass with a half power frequency of 850 nm) is used in front of the lens to cut down background noise from ambient light.

Initial tests using a x,y table explored the calibration and sensitivity issues. Plots of amplified output voltage versus LED displacement are shown in Fig. 3. The linearity of the graph is very good with a regression coefficient of 0.999 for a first order curve fit. We also investigated the sensitivity to tip rotation. This was accomplished by rotating the LED around an axis perpendicular to the line between sensor and LED. The result is also displayed in Fig. 3. The slope of the three graphs is identical, while the offsets of the graphs differ. A ten degree twist changes the output voltage by 1 volt. Since the actual tip rotation is much smaller (« 1 degree) the influence of the tip rotation on the deflection measurement is negligible. A last test addressed the sensitivity orthogonal to the measurement axis. This is important since the active sensor area is a narrow strip of 4 mm width. The field of view in this direction is approximately 38 mm . The noise level is quite high on the boundary leaving a 14 mm wide band in the middle for measurements. In this area the voltage is constant and the noise low.

Therefore it is important to align sensor and LED carefully. We decided to calibrate the sensors on the manipulator and designed appropriate sensor and LED mounting devices. Those devices allow for the adjustment of three rotations and the positioning of the LED in two directions. The unknown relation between voltage and link deflection can be determined by changing the LED position relative to the link which is kept in constant position. Due to gravity the links are deflected during calibration which adds an unknown offset. The sensor output exhibits little noise as can be seen from Fig. 4 which exhibits plots of variance versus calibration position.

4. EVALUATION OF MEASUREMENT METHOD

4.1. Comparison with static deflection model

We developed a static deflection model of RALF for two purposes. First to evaluate the measurement method and second to separate static and dynamic deflection components of measurements taken. For this model we segmented the flexible links in sections with constant cross-section and used elementary beam theory to derive deflection equations for each section. Reactions between the members of the manipulator structure and distributed gravity loading were considered. The model computes the deflection of both links as a function of manipulator configuration (two joint angles) and payload attached to the tip.

To compare deflection model and deflection measurement we moved the manipulator to four configurations and varied the tip payload. No servo control was necessary to maintain the manipulator position, since the four configurations are located in corners of the workspace . The observed deflections should therefore be pure static structural deflections.

Resulting deflection plots are shown in Fig. 5. Note that the link deflection indicated is relative to the calibration position (home position). Comparing the deflection graphs for each link we note that the slope of model and measurement is approximately the same at each individual configuration. However the difference between the offsets varies greatly. (Note that an offset was added to all sensor data so that the initial link deflection at the calibration position is identical to the model deflection.) This result would indicate a good measurement of local or relative position but a less good measurement of absolute position.

4.2. Comparison with relative position measurement

To further evaluate the measurement method we compared tip deflection measurements (evaluated from joint angle and link deflection measurements) with relative measurements taken with a dial indicator. The experimental procedure was similar to the above mentioned procedure except that we had to limit the experiment to the first two configurations in order to reach the manipulator tip and read the dial indicator. The dial indicator was aligned to directly measure the tip deflection in vertical direction. The combined tip deflection measurement using the sensors on the manipulator represents the deflection component in vertical direction.

The resulting tip deflection plots are shown in

Fig. 6. Note that the offsets at zero-payload are arbitrary. The third and fourth graphs are based on the static deflection model. The data points labeled "Model" represent the model described in the previous section. The data points labeled "Model 2" represent an extended static deflection model which includes an additional base deflection component. The tip deflection curves for both models and the sensor measurement in home position have almost identical slope and the two curves based on the models are identical. The deflection curve of the dial indicator shows a larger manipulator compliance than the other curves.

When the manipulator is moved from home position to the extended position the situation changes. Sensor measurement and model without base deflection component continue to have the same slope, while the curve for the model considering base deflection approaches the curve of the dial indicator. This indicates that a noticeable base deflection occurs when the center of gravity of the manipulator is moved away from the base (This can also be noticed by inspection of the base plate , which was bent slightly from years of experiments). The measurement based on the link deflection sensors is not able to detect this deflection component.

Modification of the base to increase stiffness marginally improved the results from the link deflection sensor as shown in Fig. 7. (Note that offsets are added so that all graphs start at zero deflection.) The third curve presented in this plot is the direct measurement of tip position using a solid state camera integrated with a computer. This integrated landmark tracking system has the advantage of direct measurement of the deflection relative to the environment but has the disadvantage that measurements are available at a limited rate of about 10 readings per second.

5. CONCLUSIONS

The present system is capable of relative position measurements which is indicated by the similarities between the slopes of the deflection curves in Fig. 5. Numerical differentiation of the deflection measurement should yield a clean signal, since the measurement noise is very low (Fig. 4). The relative position measurement provides feedback for relative positioning of the manipulator end-effector or compensation for variable payload.

The discrepancy between the link deflection sensors and direct end-point position measurements appears to be due to base and actuator mounting compliance. Total elimination of this error does not seem possible, although independent sensing of base motion may be feasible. The large arm radius renders tip position extremely sensitive to base rotational compliance.

The link deflection sensors are well suited to enhancing the direct end-point measurement by landmark tracking cameras. The slow sample rate from the camera is offset by fast sampling of the high bandwidth analog link deflection sensors. These sensors will be combined using multi-rate Kalman filtering in future research.

Acknowledgements
This work was partially supported by Sandia National Laboratory and Pacific Northwest Laboratory under contract 18-4379G through the Robotics Technology Development Program.

6. REFERENCES

Ballhaus, W.L. and Rock, S.M. (1992) "End-Point Control of a Two-Link Flexible Robotic Manipulator with a Mini-Manipulator: Initial Experiments", *Proceedings of the American Control Conference*, Vol.3, Chicago, IL, June 24-26, pp.2510-2514.

Cannon, R.H., Jr. and Schmitz, E. (1984) "Initial Experiments on the End-Point Control of a Flexible One-Link Robot", *The International Journal of Robotics Research*, Vol. 3, No. 3, Fall 1984, pp. 62-75.

Lee, H.G., Kawamura, S., Miyazaki, F., and Arimoto, S. (1990) "External Sensory Feedback Control for End-effector of Flexible Multi-Link Manipulators", *Proceedings of the 1990 IEEE International Conference on Robotics and Automation*, Vol.3, Cincinnati, Ohio, USA, May 13-18, 1990, pp.1796-1802.

Morikawa, H., Takanashi, N., and Tagawa, N. (1992) "A Telerobot System for Space Antenna Assembly Experiments", *Proceedings of the 1992 IEEE International Workshop on Intelligent Robots and Systems*, 1992.

Morikawa, H., Takanashi, N., Tagawa, N., and Fukuchi, H. (1990) "A Prototype Space Telerobotic System", *Proceedings of the 1990 IEEE International Workshop on Intelligent Robots and Systems*, Tuchiura, Japan, 1990, pp.421-428.

Nam, Y. and Dickerson, S.L. (1991) "Position Estimation with Accelerometer and Vision Measurement", *Advances in Instrumentation*, DSC-Vol.30, 1991 ASME Winter Annual Meeting, Atlanta, Georgia, USA, December 01-06, 1991, pp.1-8.

Oakley, C.M. and Barratt, C.H. (1990) "End-Point Controller Design for an Experimental Two-Link Flexible Manipulator Using Convex Optimization", *Proceedings of the 1990 American Control Conference*, Vol.2, San Diego, California, USA, May 23-25, 1990, pp.1752-1759.

Oakley, C.M. and Cannon, R.H., Jr. (1989) "End-Point Control of a Two-Link Manipulator with a Very Flexible Forearm: Issues and Experiments", *Proceedings of the 1989 American*

Control Conference, Vol.2, Pittsburgh, Pennsylvania, USA, June 21-23, 1989, pp.1381-1388.

Obergfell, K. and Book, W.J. (1992) "End-Point Control of a Two-Link Flexible Manipulator using the Landmark Tracking System", *Proceedings of the Japan-USA Symposium on Flexible Automation*, Vol.1, San Francisco, CA, July 13-15, pp.701-706.

Rattan, K.S., Feliu, V., and Brown, H.B., Jr. (1990) "Tip Position Control of Flexible Arms Using a Control Law Partitioning Scheme", *Proceedings of the 1990 IEEE International Conference on Robotics and Automation*, Vol.3, Cincinnati, Ohio, USA, May 13-18, 1990, pp.1803-1808.

Wang, D. and Vidyasagar, M. (1987) "Control of a Flexible Beam for Optimum Step Response", *Proceedings of the 1987 IEEE International Conference on Robotics and Automation*, Vol.3, Raleigh, North Carolina, USA, March 31 - April 3, 1987, pp.1567-1572.

Wang, W.J., Lu, S.S., and Hsu, C.F. (1989) "Experiments on the Position Control of a One-Link Flexible Robot Arm", *IEEE Transactions on Robotics and Automation*, Vol. 5, No. 3, June , pp. 373-377.

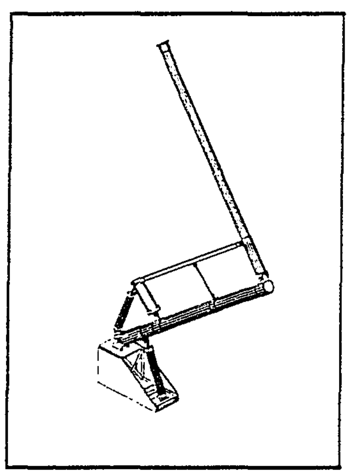

Fig. 1. Two-link flexible long-reach manipulator denoted RALF

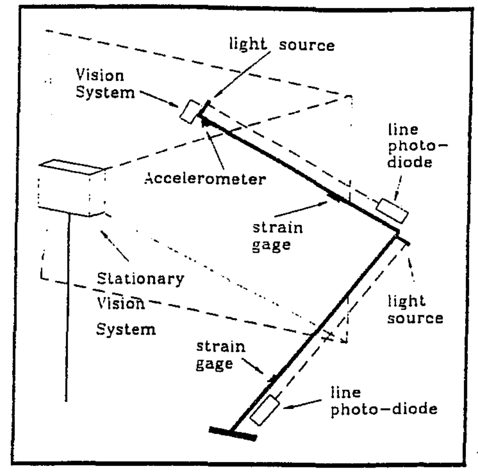

Fig. 2. Location of sensors on RALF

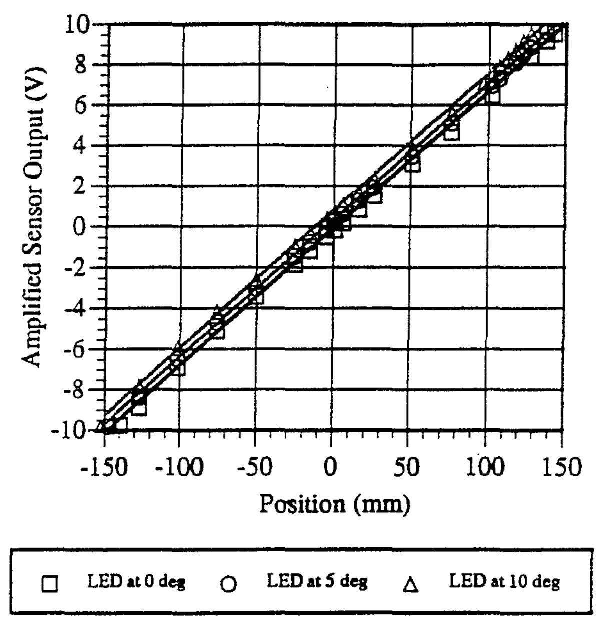

Fig. 3. Linearity and sensitivity to rotation of position measurement using lateral-effect photodiode

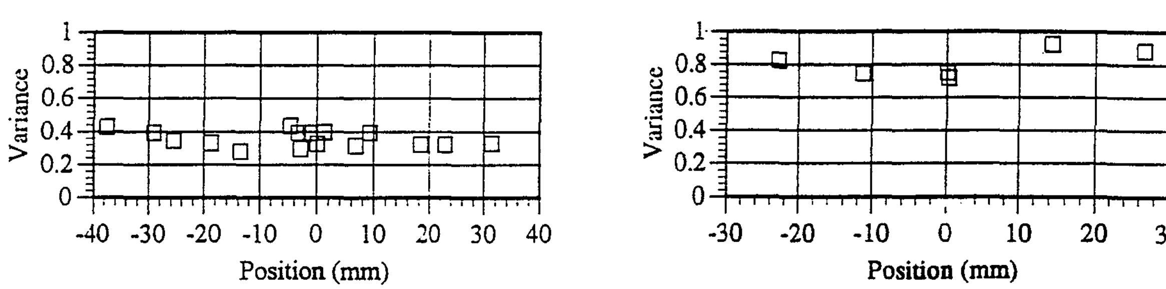

Fig. 4 Noise of position measurements using lateral-effect photodiode (left lower link, right upper link)

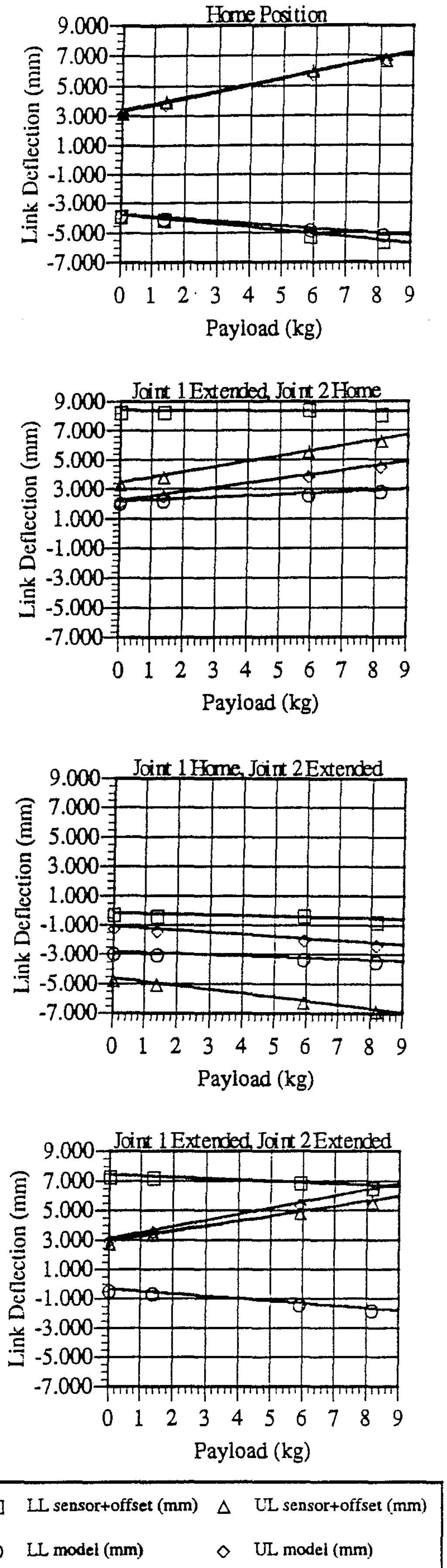

Fig. 5. Link deflection comparison for 4 manipulator positions using deflection sensors and static deflection model

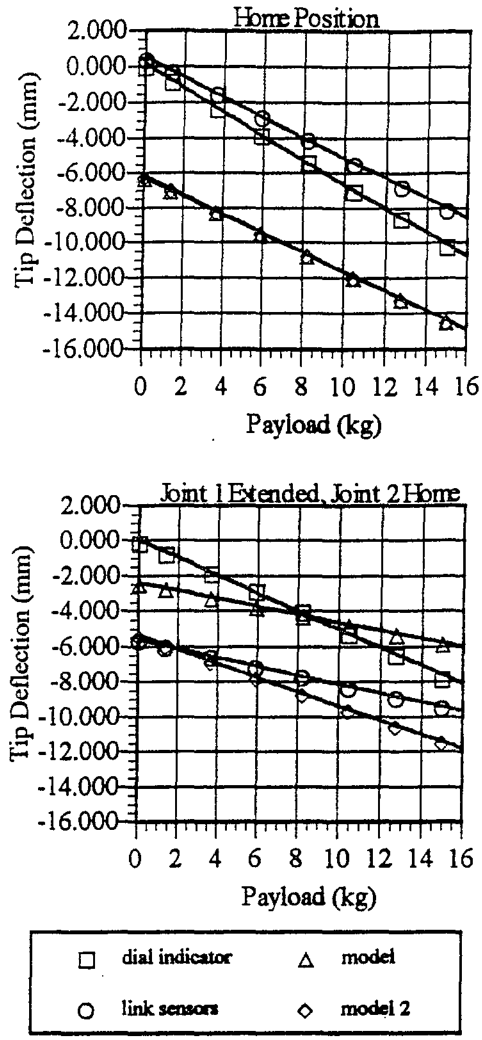

Fig. 6. Tip deflection comparison for 2 manipulator positions using dial indicator, deflection sensors and 2 static deflection models

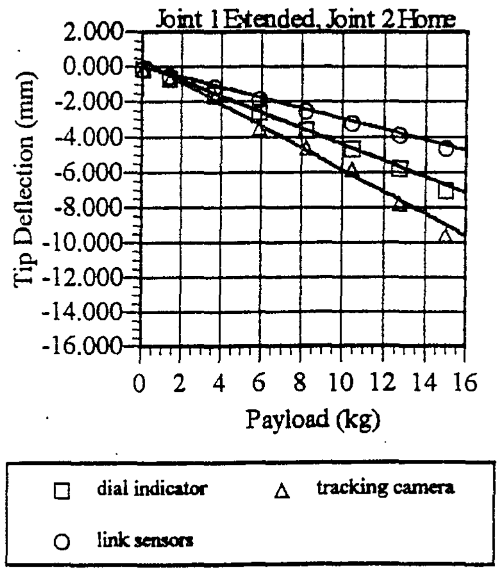

Fig. 7. Tip deflection comparison after stiffening manipulator base using dial indicator, deflection sensors and landmark tracking camera