Dynamics of a Planar Arm Model with Servo-regulated Viscoelastic Muscles in a Microgravity Environment

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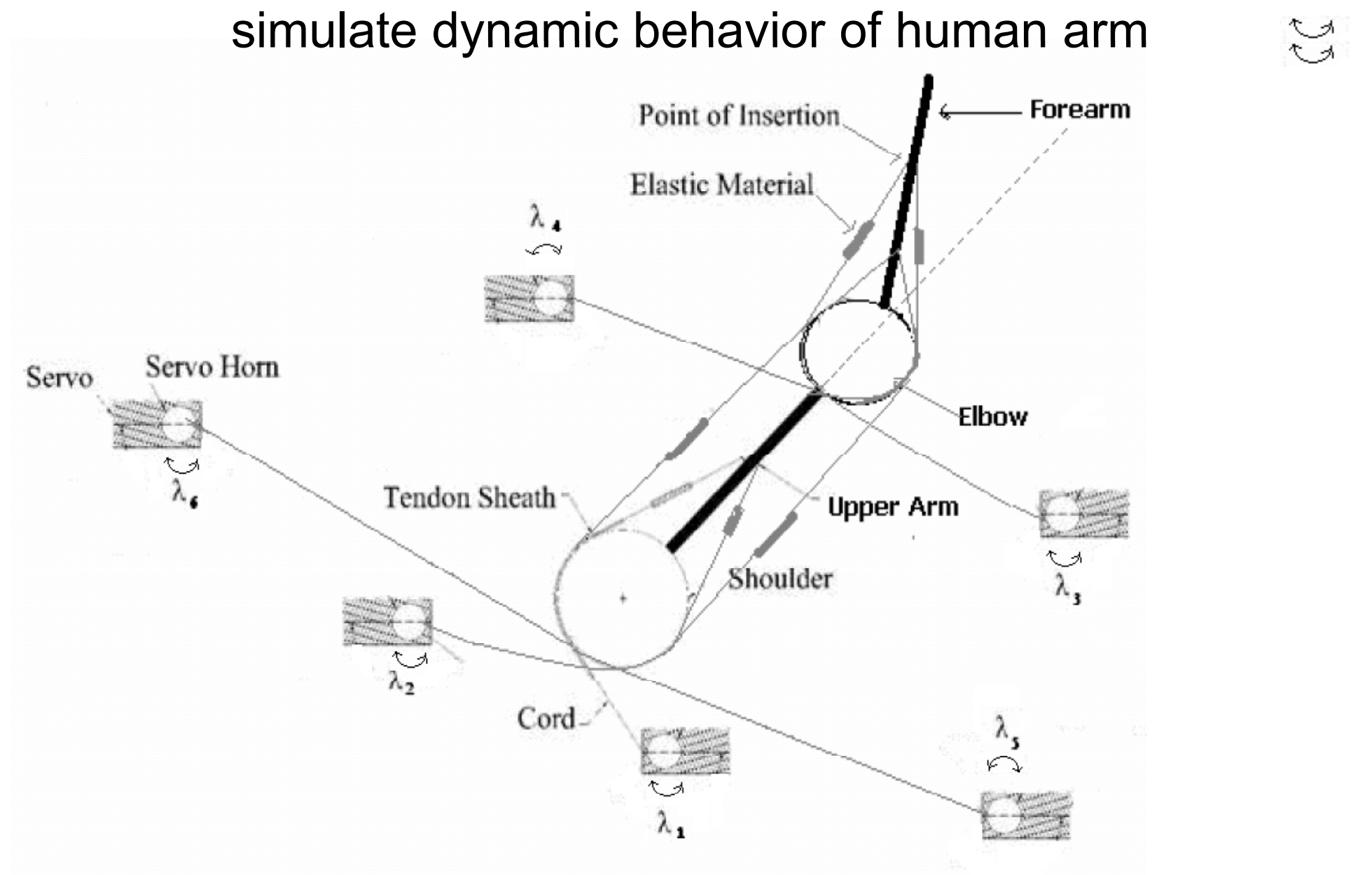
Abstract

We constructed a mechanical arm model consisting of a rigid upper arm and forearm which simulates vertical planar arm motion with two degrees of freedom: shoulder rotation and elbow rotation. Computer controlled servo-motors effect rotation of the elbow and shoulder joints through tensions incited in elastic materials which represent muscles. We predicted and then observed vertical planar arm motion in the laboratory under normal Earth gravity conditions, and on NASA's Weightless Wonder in near zero gravity conditions. Because the arm only has two degrees of freedom we were able to simulate near zero gravity in the laboratory and predict the subsequent motion by operating it in the horizontal plane. We will discuss results of the actual observed motion in these three environments, and compare them to the motion predicted based on the equations of motion. We will also discuss how the project was developed physically, mathematically, and electronically.

Introduction

- Many different physical models of the human arm have been built and tested.
- All these models use gears or pulleys and do not explicitly model the actual tendons and muscles that move a human arm.
- We built and tested a model of the human arm that explicitly models the tendons as strings and the muscles as stretchable rubber tubes.

Simplified representation of mechanical arm designed to simulate dynamic behavior of human arm

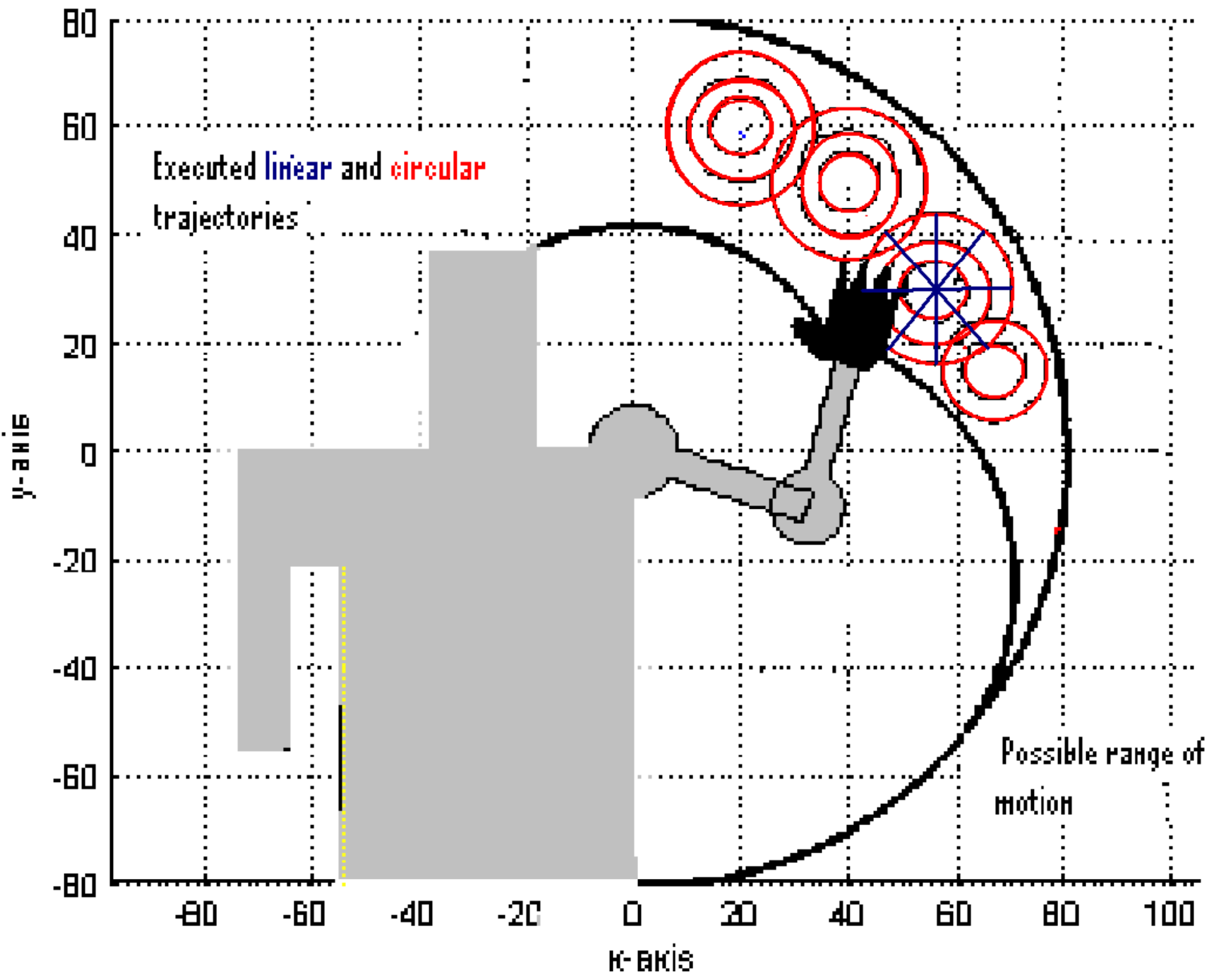


Constructed Arm Model

Analytical Method

- **Choose a particular trajectory the arm will execute.**
  1. linear 2. circular

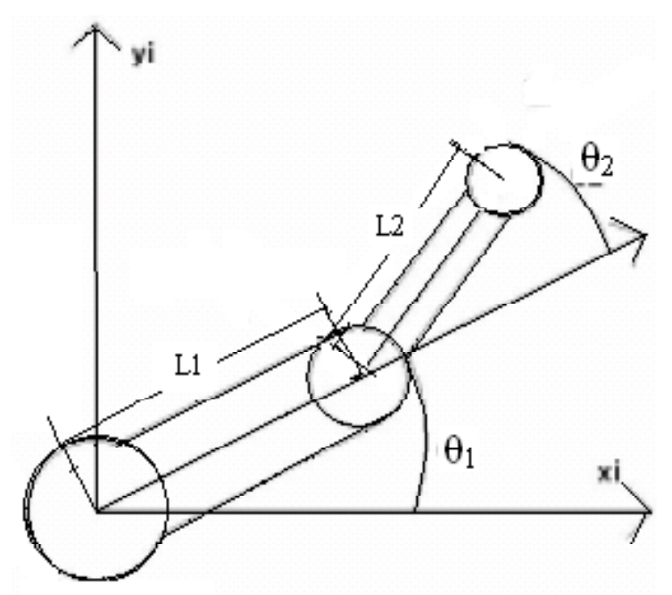
Executed Trajectories



- Convert Cartesian coordinates of trajectory into θ values:

$$\theta_1 = \tan^{-1}\left(\frac{y}{x}\right) - \tan^{-1}\left(\frac{L_2 \sin\theta_2}{L_1 + L_2\cos\theta_2}\right)$$

$$\theta_2 = \cos^{-1}\left(\frac{x^2 + y^2 - L_1^2 - L_2^2}{2L_1L_2}\right)$$



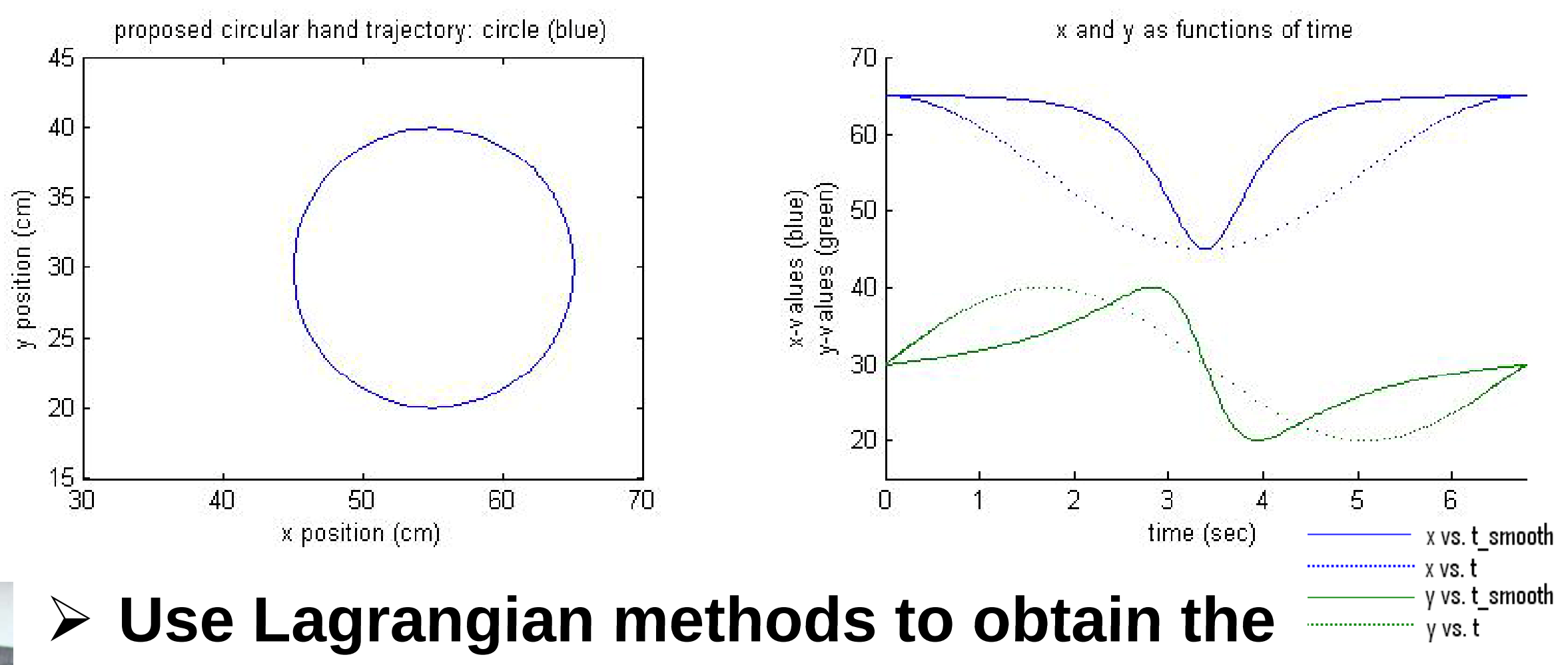
- **"Smooth Time"**
  - Introduce the "smooth time" to eliminate the "infinite acceleration" at starting and ending points

$$t_{smooth} = \frac{1}{2}\left\{1 + \frac{\tan^{-1}[f \cdot (\frac{t - t_0}{t_0})]}{\tan^{-1}(f)}\right\} \cdot t_{end}$$

Where t_{end} *is the ending time of the motion;*

$t_0 = \frac{t_{end}}{2}$*; and* f *is the smooth factor*

Kinematics Analysis of a Possible Circular Hand Trajectory



- **Use Lagrangian methods to obtain the equations of motion of the arm:**
  - The potential energy of the arm has both a gravitational (U_g) and elastic (U_e) contribution
  - U_e depends on the angles of the arm segments (θ) and the stretch (λ) of the muscles:

$$U_e = \sum_{j=1}^{6} U_{e,j} = \tfrac{1}{2}\sum_{j=1}^{6} k_j\,\Delta l_j^2$$

  - U_e (energy stored by the muscles) is determined by summation using Hooke's Law for each muscle:

$$U_e(\theta_1, \theta_2, \lambda_{j=1,2,\ldots,6}) = \sum_{j=1}^{6} U_{e,j}(\theta_1, \theta_2, \lambda_j)$$

- Net torques required on the two arm segments are then given by:

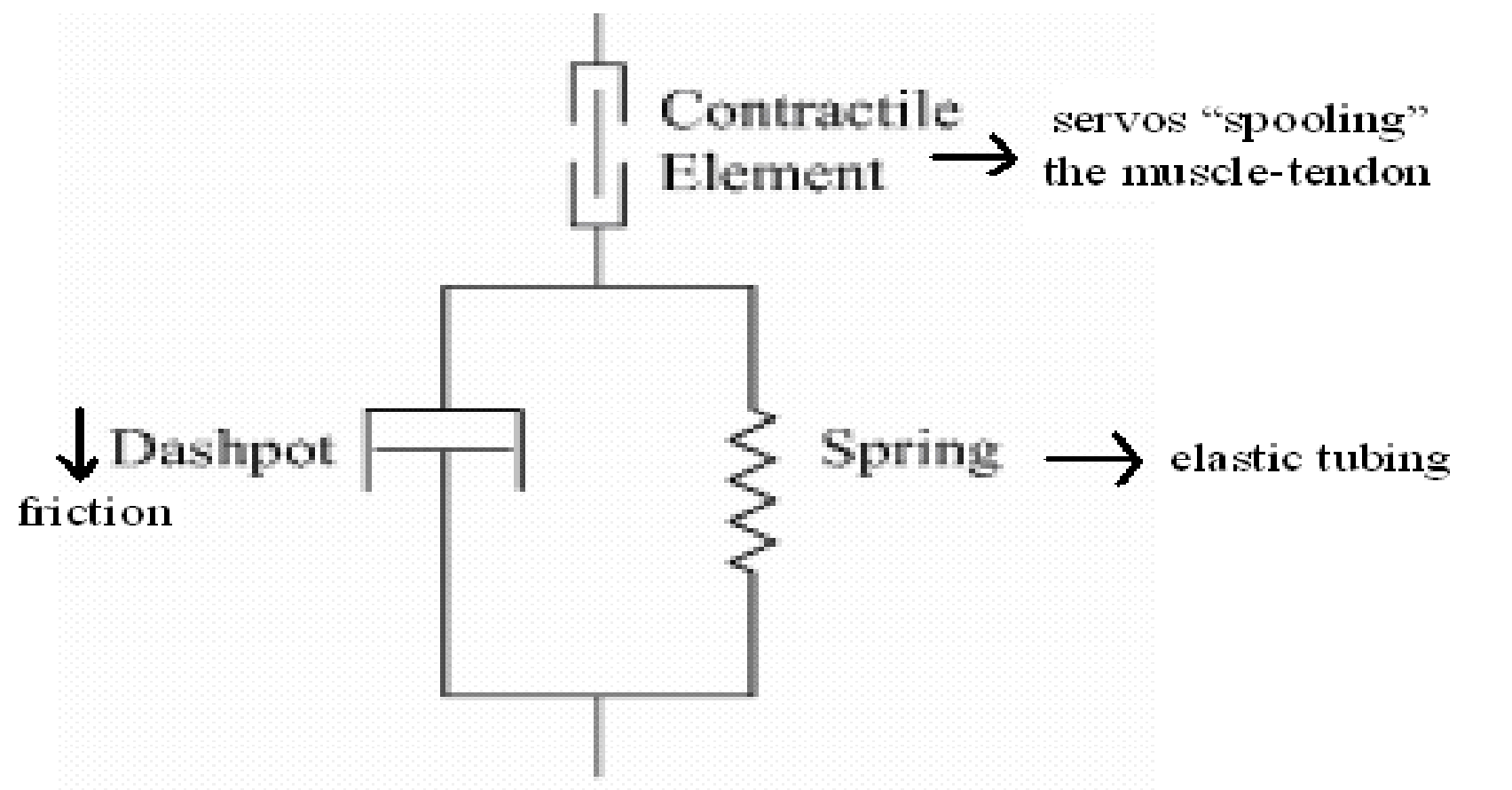
$$\tau_{1e} = -\frac{\partial U_e}{\partial \theta_1} = -\sum_{j=1}^{N}\frac{\partial U_{e,j}}{\partial \theta_1} = -\sum_{j=1}^{N} k_j\,\Delta l_j \frac{\partial \Delta l_{j_e}}{\partial \theta_1}$$

$$\tau_{2e} = -\frac{\partial U_e}{\partial \theta_2} = -\sum_{j=1}^{N}\frac{\partial U_{e,j}}{\partial \theta_2} = -\sum_{j=1}^{N} k_j\,\Delta l_j \frac{\partial \Delta l_{j_e}}{\partial \theta_2}$$

- **Finally, convert muscle forces into servo angles using Hooke's law relationships:**

$$\begin{bmatrix} f_1(\Delta l_1) \\ f_2(\Delta l_2) \\ f_3(\Delta l_3) \\ f_4(\Delta l_4) \\ f_5(\Delta l_5) \\ f_6(\Delta l_6) \end{bmatrix} = \begin{bmatrix} k_1(R_h\lambda_1 - R_s(\theta_1 - \theta_{11})) \\ k_2(R_h\lambda_2 + R_s(\theta_1 - \theta_{12})) \\ k_3(R_h\lambda_3 - R_e(\theta_2 - \theta_{23})) \\ k_4(R_h\lambda_4 + R_e(\theta_2 - \theta_{24})) \\ k_5[R_h\lambda_5 - R_s(\theta_1 - \theta_{15}) - R_e(\theta_2 - \theta_{25})] \\ k_6[R_h\lambda_6 + R_s(\theta_1 - \theta_{16}) + R_e(\theta_2 - \theta_{26})] \end{bmatrix}$$

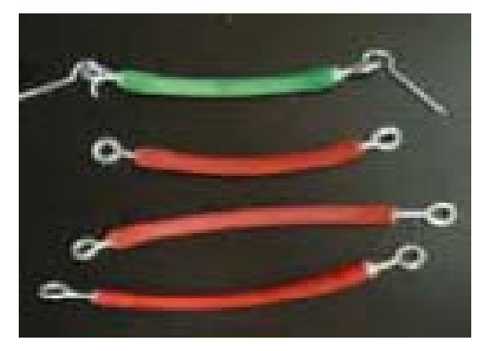
Experimental Method



Our mechanical arm's muscles resemble a Kelvin-Voigt viscoelastic element in series with a contractile element.

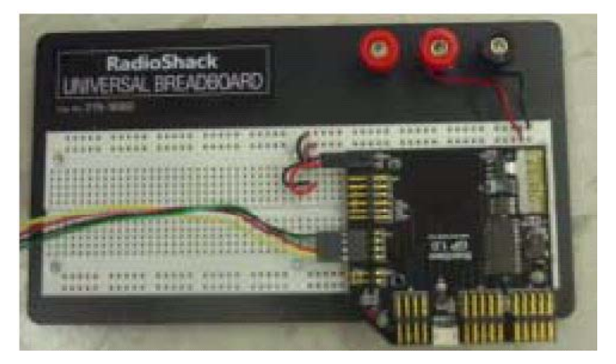
- Tendons are simulated by strong fishing line

- Muscles are simulated by elastic Thera-Brand tubing and attached to the tendons by interlocking hooks



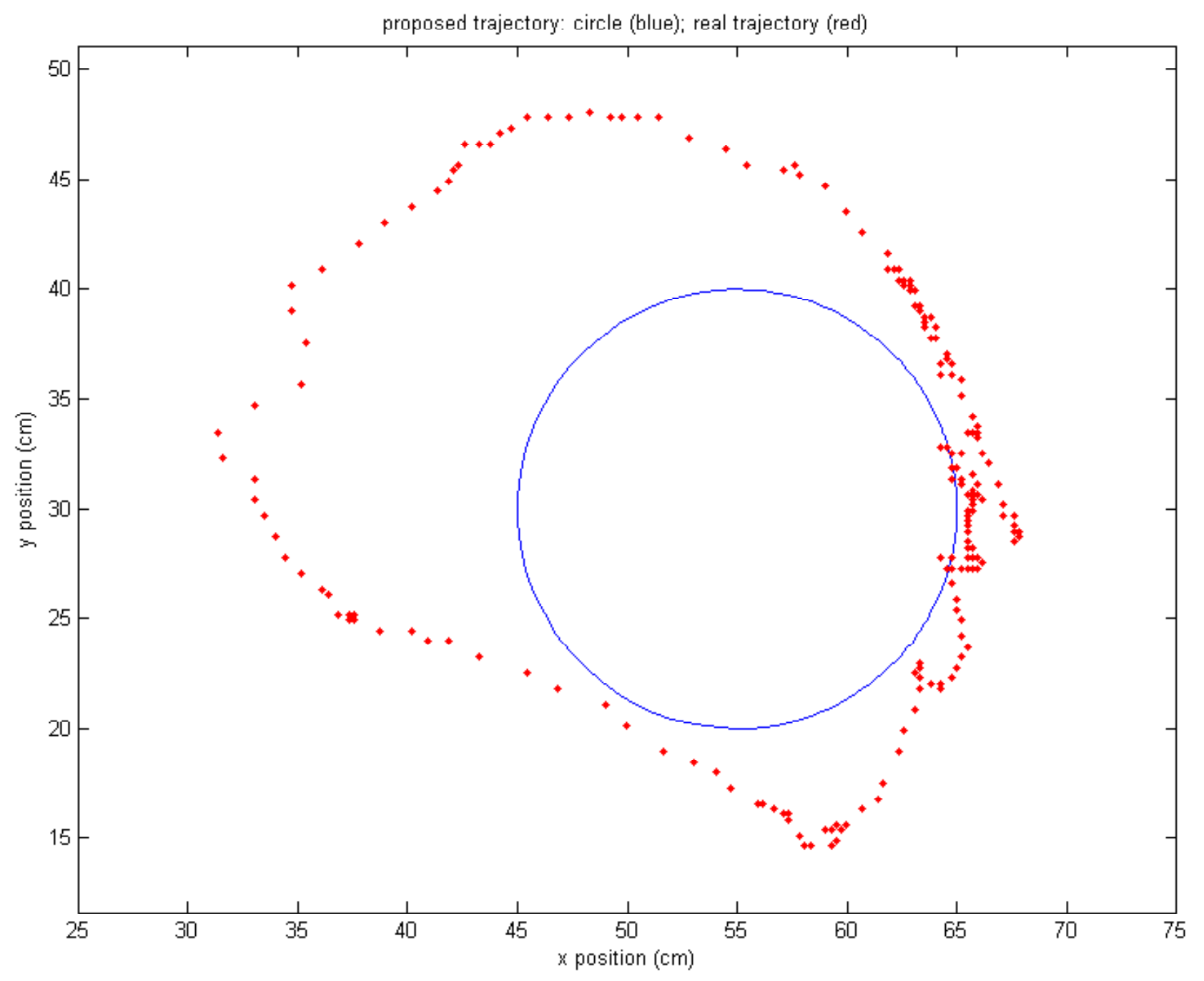
- Digital Servos with 136 oz-in of torque, with 720 degrees of possible rotation, provide muscle contractions

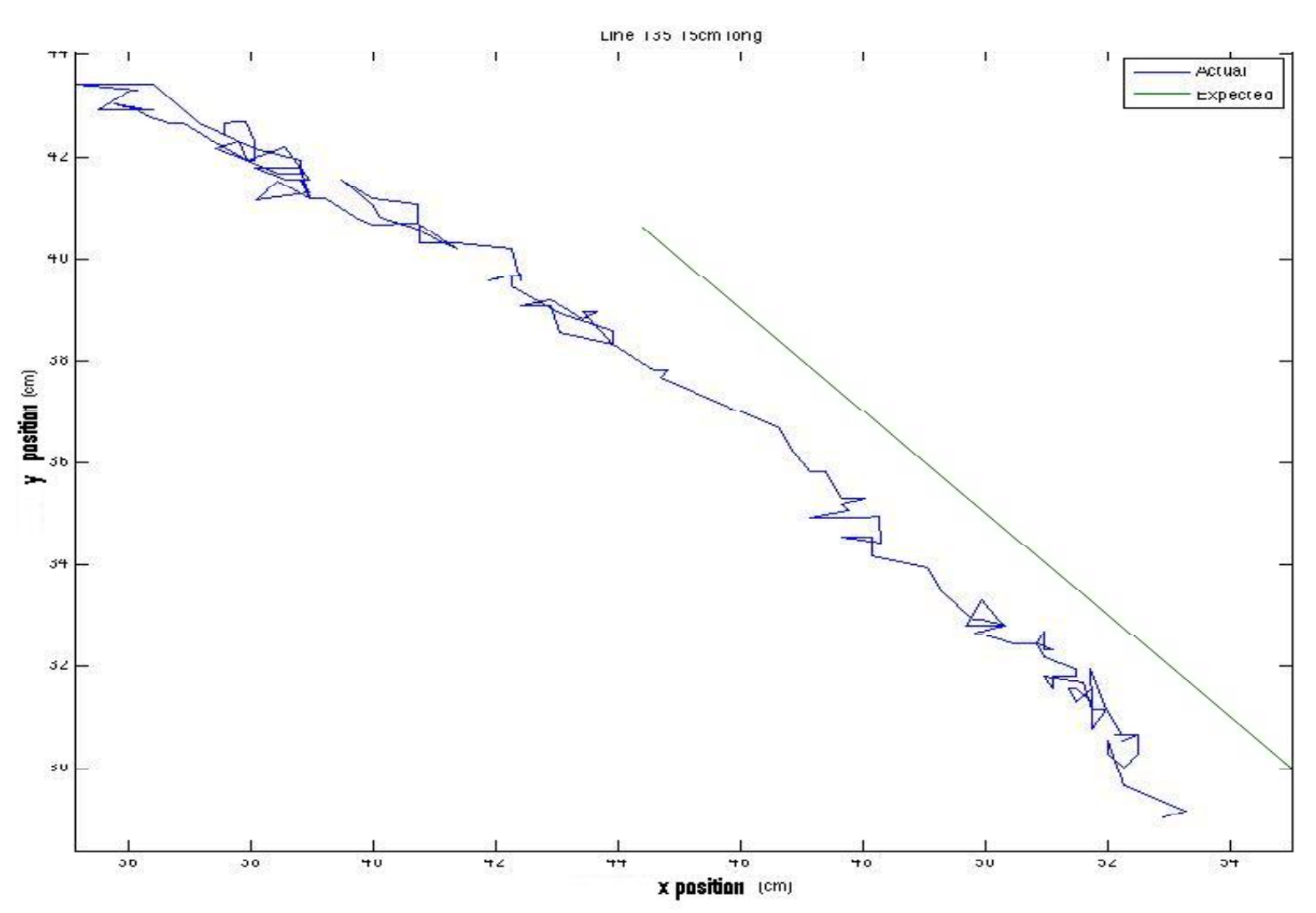
- Servos are controlled using two General-Purpose Brainstem.

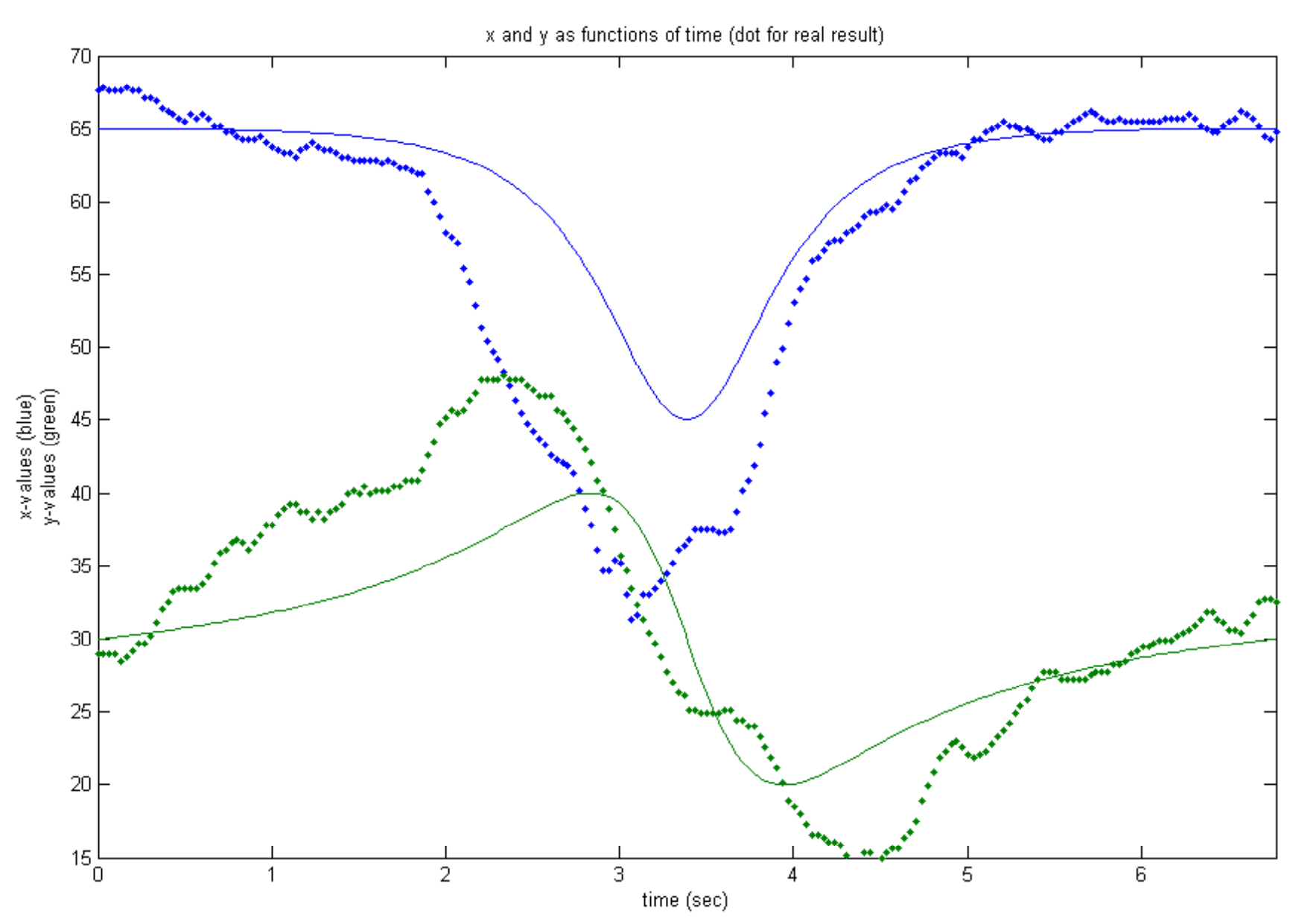


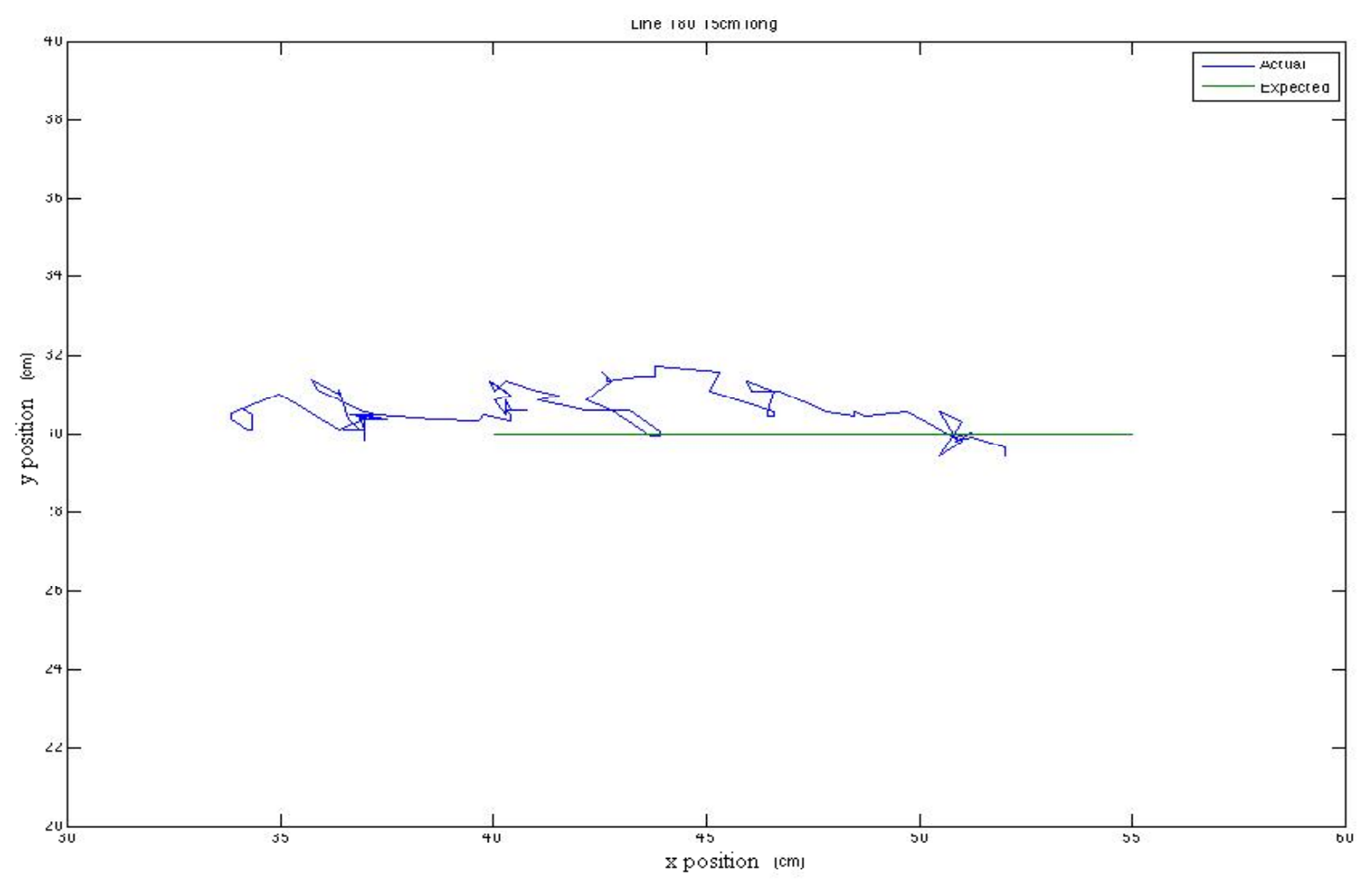
- The angles of rotation of the shoulder and elbow joints are recorded using angular motion sensors (potentiometers).
- Prescribed time sequences of servo angle rotation commands are sent to the brainstem using the C programming language.
- Numerical integrations are performed using Matlab.

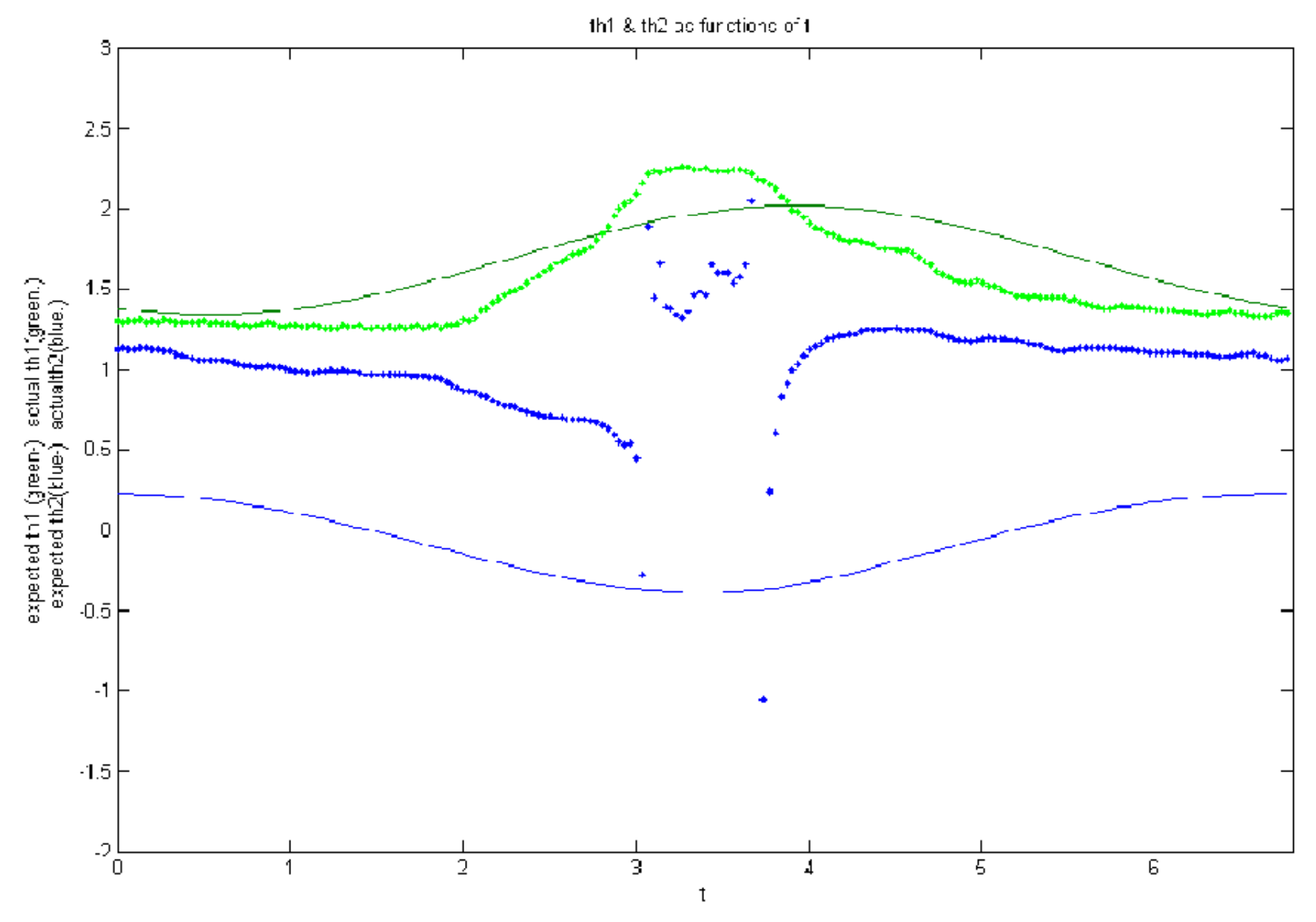
Results











Analysis

- We noticed the most variation between expected values and experimental results in our values for theta. The trend of the experimental theta values are in line with the expected values, but inaccurate. Due to the large variations in th2 values on the interval 3s < t < 4s it appears that the servo that controls the fore arm has some mechanical issues.

Conclusions

- The physical model of the arm was found to be quite successful in representing two degrees of freedom planar arm motion .
- The motion of the arm was not as smooth as predicted due to friction within the elbow and shoulder joints and the friction caused by the contact interaction between the pivots and the shoulder and elbow.
- The sensors used for data analysis have revealed a need for higher quality equipment better suited to the environment.
- The torques provided by the servos were not sufficient to operate the arm's full range of motion in a normal gravity environment.

Future Research

The project as a whole was a success because the experience and data analysis will further our research and allow us to expand our project, adding a 3rd degree of freedom to our human arm proxy. Beyond the physical model, which must change to allow for improved operation, we are now prepared to further develop our analytical model in order to take and analyze useful data in the time and environment allotted on future flights of NASA's low-g plane.

Acknowledgements

A special thanks to NASA for providing us with such an amazing educational opportunity.

–Poster made by: Jared Durden –Edited by Xiaoou Wang, Biye Li, Victor Akunyili