Design of Controller for Crawling to Sitting Behavior of Infants

A Report submitted for the Semester Project
To be accepted on: **29 June 2007**

by

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Acknowledgements

First and foremost, I would like to thanks Ludovic Righetti for his help throughout this project, particularly in constructing equations of Dynamical system and feedback on the report. I am also thankful to Professor Auke Jan Ijspeert for allowing me to do my semester project with BIRG , motivating me by showing interest in the project and giving useful suggestions for the project.

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Chapter 1

Introduction

1.1 Problem Description and Main Objectives

The RobotCUB European project [1] aims to study cognitive abilities of a child by building a 2 year old infant-like humanoid robot named iCub. The project has two main goals: first, to create an open and freely available humanoid platform for research in embodied cognition, and second, to study cognitive development. To achieve the goal of cognitive development, it is essential that the robot is able to explore its environment by crawling and sitting just like infants. Therefore, as a part of RobotCUB project, BIRG, EPFL is designing a controller for the locomotion of the robot so that it is able to crawl on its hands and knees just like an infant and should be able to make transition from crawling to sitting position and vise versa.

Controller for locomotion of robot in unpredictable environments is quite a challenging task. The main strength of locomotion of infants lies in the fact that infants are able to do locomotion robustly in almost any kind of environment. It may be possible to design very efficient controllers for locomotion when the external environment is known but such controllers do not have the capability of robust locomotion in new and unpredictable environment. Therefore, understanding the biological mechanisms of locomotion is the key for development of controllers for robust locomotion of autonomous robots. The underlying biological mechanisms by which infants are able to crawl and sit in almost any kind of environment can be learned by modeling the behavior of infants.

A controller for crawling behavior of robot has already been developed in [2] by observation of crawling in real infants. It is based on CPGs which are neural circuits responsible for locomotion found in spinal cord of animals. To design the controller first the crawling behavior of infants was studied and important characteristics of the trajectory were extracted. Then a mathematical model of CPGs based on coupled nonlinear oscillators was developed to reproduce the crawling gait of infants.

The goal of this project is to study the transition from crawling to sitting in infants and to finally design a controller for the robot that would enable it to perform this transition in the same way as infants. All the experiments on the robot are done in Webots, a simulation software [3].

1.2 Proposed Solution

For designing a controller for crawling to sitting, a biologically inspired approach is followed.

- First, the transition from crawling to sitting in real infants is studied qualitatively.

- From the qualitative observation of real infants sitting, a hand-made trajectory for the DOFs of the robot is designed such that the robot can sit.

- Then the main characteristics of the trajectory are studied. For example:

- Is the position of the projection of the center of mass of the robot on the ground, always in the support polygon?
- When is the robot unstable?
- What is the state of the robot when entering these instability regions?
- What are the critical times of the movement?

- After this, the trajectories are optimized to increase the stability of the transition

- After an optimum trajectory is made, a dynamical system can be implemented for the transition from crawling to sitting by integrating it with the previously designed controller for crawling [2].

1.3 The Robot

The detailed specifications of the real ICUB robot have been given in [4]. The Webots model of ICUB has 27 degrees of freedom: 6 in the head (3 in the neck for tilt, swing and pan and 3 in the eyes), 5 in each leg (3 in hip joint for flexion/extension, abduction/adduction and rotation and one each in knee and ankle for flexion/extension), 4 in each arm (3 in shoulder for flexion/extension, abduction/adduction and rotation and one in elbow for flexion/extension) and 3 in the torso (roll, pitch and yaw) (Fig 1.1). The real ICUB has 53 degrees of freedom with extra degrees of freedom in hand and wrist but for simulation of crawling and sitting behaviors the 27 degrees of freedom in the Webots model of ICUB are sufficient.

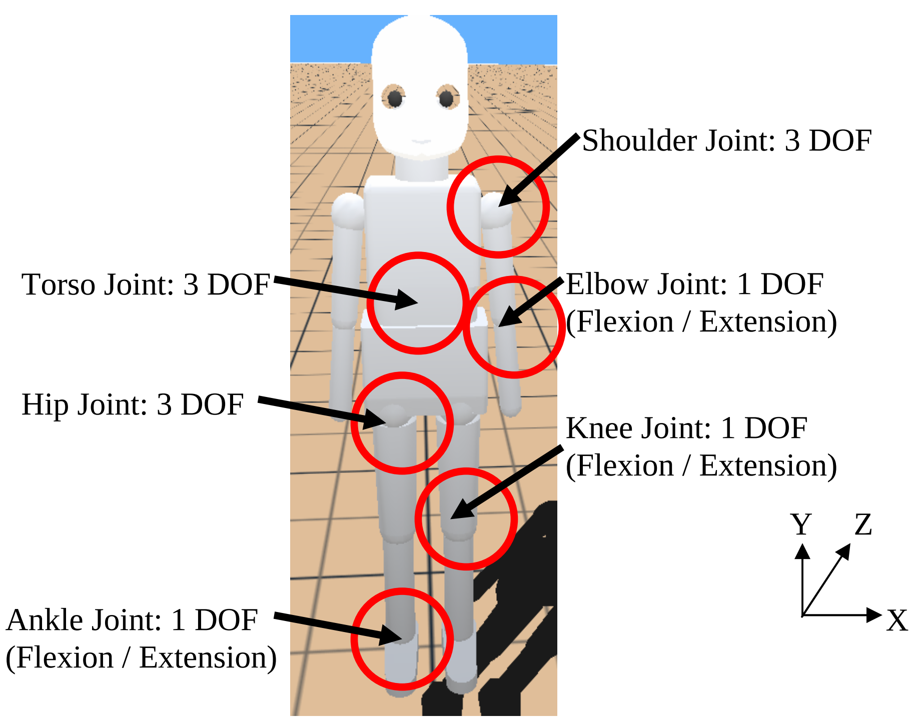


Figure 1.1: The degrees of freedom in the Webots model of the ICUB

The range of motion of joint angles (in radians) used for sitting and crawling along with the names used for those angles in the report is shown in Figure1.2.

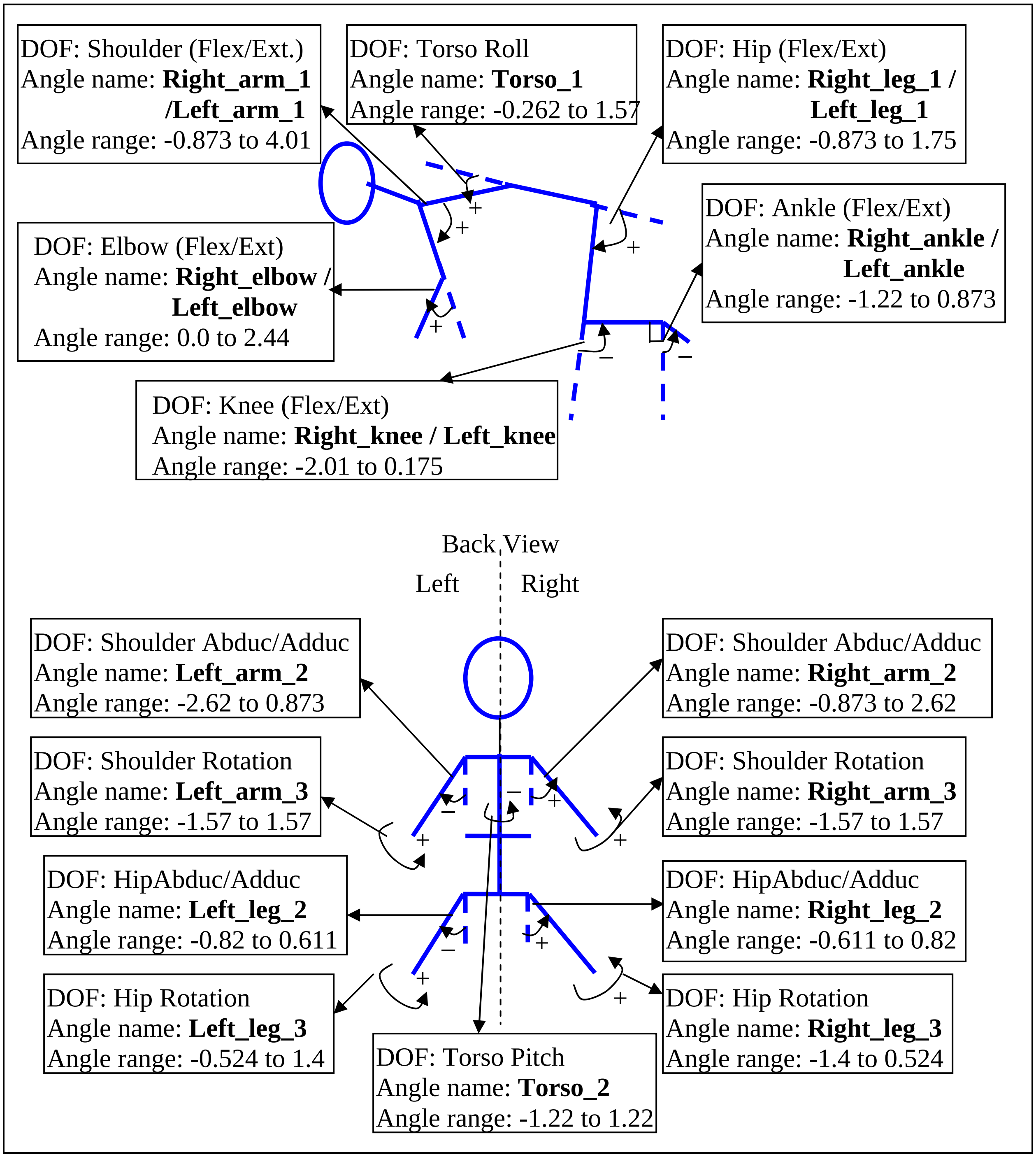


Figure 1.2: Names and range of motion of joint angles of Webots model of the ICUB

1.4 Organization of the report

In chapter 2, I will describe the qualitative characteristics of the transition from crawling to sitting observed in real infants and compare the hand-made trajectory developed for the robot with the trajectory followed by real infants. Then, I will analyze the main characteristics of the hand-made trajectory and explore the various stability criteria for the trajectory. In chapter 3, I will describe how we can switch from crawling to sitting controller when an external signal is provided and how we can generate the trajectories for sitting from a dynamical system.

Chapter 2

Development of hand-made trajectory

2.1 Observations from real infants

The study of crawling to sitting in real infants was done on the kinematical data of crawling babies provided by Uppsala University (Sweden) to BIRG, EPFL. The data contains recorded videos of about 1 year old infants crawling on the ground, shifting to sitting from crawling and from crawling to sitting.

From the videos, it was observed that infants generally sit in two ways as shown in Figure 2.1. In the first way (Figure 2.1a), infants sit on their legs while in the second way (Figure 2.1 b), infants sit on their hips. The first method of sitting is not adequate for robots as it puts lot of pressure on knee and ankle joints. Also the knee needs to be flexed towards hip to a large extent which is not achievable in the real iCUB robot. Therefore, the second method of sitting has been studied for the development of hand-made trajectory.

(a) (b)

Figure 2.1: The two ways in which infants generally sit

When infants sit on their hips, two main characteristics of the transition can be noticed:

(i) First, infants bring one of their leg forward using the other leg and arms as a support (First 3 snapshots of real infants in Figure 2.2)

(ii) Then they move their arm back and finally sit on their hip(Last 3 snapshots of real infants in Figure2.2)

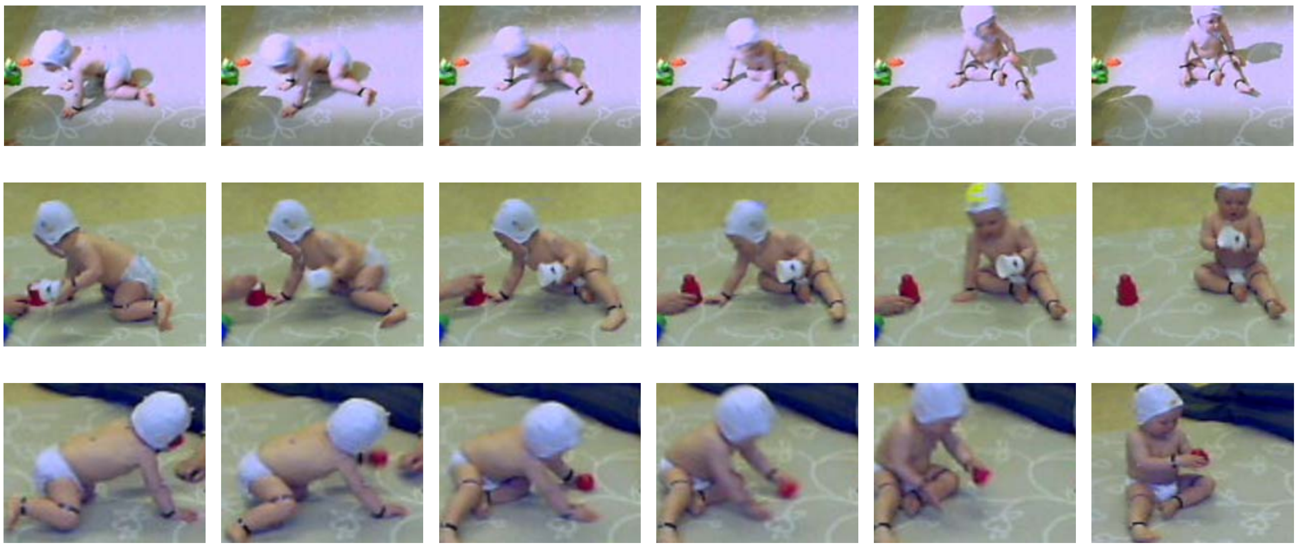


Figure 2.2: Infants doing transition from crawling to sitting

The main focus while developing hand-made trajectory has been on the capturing of these two main characteristics of the transition from crawling to sitting in infants. In Section 2.2, I will describe the hand-made trajectory developed for the ICUB.

2.2 The hand-made trajectory

The trajectory is developed by specifying the angles for Relevant DOFs after 5 TimeSteps (1 Time Step = 64 ms) and then interpolating between these angles for every TimeStep using PCHIP (Piecewise Cubic Hermite Interpolating Polynomial) [5]. This interpolation method gives an interpolating polynomial whose first order derivative is continuous. Unlike spline interpolation, the second order derivative is not continuous but the shape of data is preserved by this interpolation i.e the interval where the data is monotonic, interpolating polynomial is also monotonic (Figure 2.3).

The sitting method of the robot using the hand-made trajectory has been compared with the sitting method of real infant in Figure 2.4. The two main characteristics of the sitting method that were observed in real infants have been captured in the hand made trajectory also.

To bring one of the legs forward (left leg in this case) first the DOF Torso Pitch is moved which shifts the weight of the body to the right side (Fig 2.5 :First snapshot) Then the DOF right leg (Abduction / Adduction and Rotation) move which broadens support polygon i.e right half of the body starts supporting the body (Fig 2.5 :Second snapshot). Also simultaneously left knee starts extending so that it can come forward. While the left knee is extending, DOF left leg (Abduction/Adduction and Rotation) move. This movement of left leg helps in extension of left knee without putting much pressure on the right half of the body. If the DOF left leg (Abduction / Adduction and Rotation) do not move, the extension of knee will increase the height of left half of the body and robot may fall towards the right side. After the extension of left knee is done the DOF left leg (Abduction / Adduction and Rotation) move back to their original state and the first phase of bringing left leg forward is completed (Fig 2.5 :third snapshot). Then the right arm moves so that the robot is able to sit on the hip (Fig 2.5 : Last 3 snapshots).

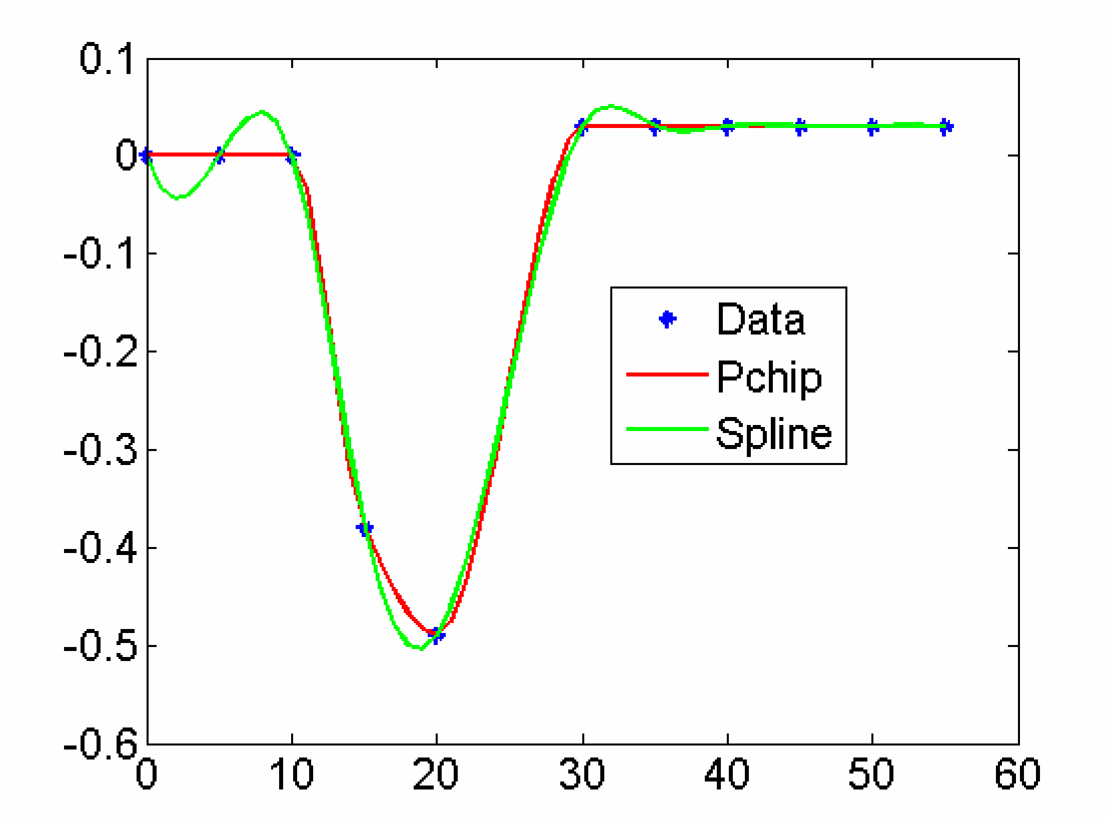


Figure 2.3: Comparison of interpolation of data using Pchip and spline interpolation

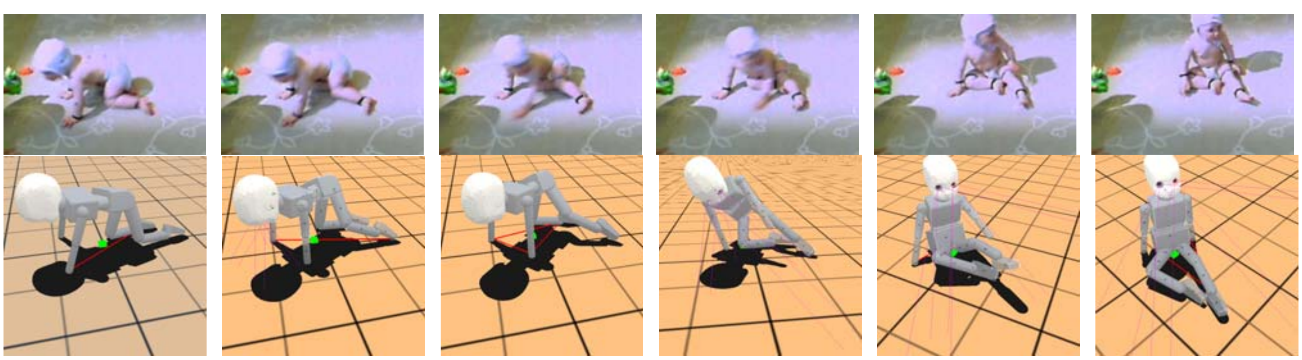


Figure 2.4: Hand made trajectory of the robot compared with real infant

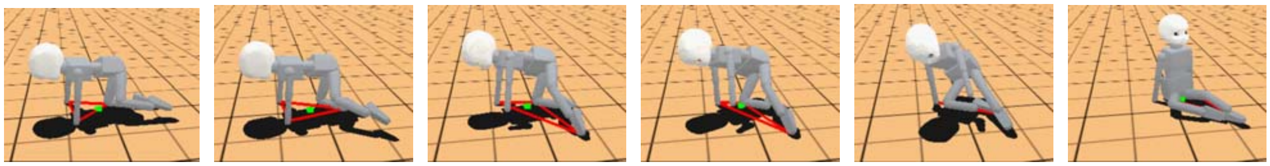


Figure 2.5: Main actions of robot while sitting. The red lines shown the support polygon and the green box shows the projection of center of mass on the ground.

Though the main characteristics of sitting transition in infants have been captured, there are some visible differences in the sitting method of infant and the robot because of the constraints on the maximum angle up to which hip joint of the robot can be extended. Real infant extend their legs to a large extent while moving one of their leg forward (Angles right_leg_1 and left_leg_1 as defined in Figure 1.2 are at least 2 radians). Because of this, the hips of the infant are almost touching the ground when the infant has brought its leg forward (First 3 snapshots of real infant in Figure 2.4) but the robot cannot extend its legs to such a large extent. The maximum range of angles right_leg_1 and left_leg_1 is 1.75 radians. Due to this constraint, hips of the robot are quite above from the ground level when it starts moving its arm back (last 3 snapshots of the robot in Figure 2.4) as compared to the real infant. This makes the robot more unstable in the second part of the transition.

In the next section, I will analyze the main characteristics of the hand-made trajectory like its stability, robustness, position of projection of center of mass etc.

2.3 Analysis of main characteristics of trajectory

2.3.1 Division into two phases

As observed in the real infant, the transition from crawling to sitting can be divided into two parts. In the first part, child brings one of its legs to the front by using second and third degrees of freedom of leg. After that, child moves its arm backward in order to sit on the ground.

The variations of joint angles of relevant DOFs of robot while sitting are shown in Figure2.6. The yellow line (left most) in the plots corresponds to the point when robot starts rotation of its leg in order to bring it forward (left leg in this case). The orange line (middle) corresponds to the point when robot has completed the rotation of its left leg and starts moving its right arm so that it can sit. The red line (right most) corresponds to the point when robot sits on the ground.

If the trajectory is specified only until orange line (middle), then robot does not sit but is stable at its position and right arm can be moved at any time to make the robot sit. Therefore there is a clear distinction between two phases.

The projection on the ground of the center of mass of robot is inside the support polygon during the first phase and goes outside the support polygon during the second phase. We can say that the second phase is the *critical period* while making transition from crawling to sitting because during this period the robot is unstable. This is also indicated by the torso speed of the robot (plotted in solid black line with the variation of joint angles with time in Figure 2.6) which goes to its maximum value during the second phase.

In the next section, I will explain the method of checking the robustness of the sitting transition using the *critical period* to limit the parameter space and analyze the robustness of the current trajectory.

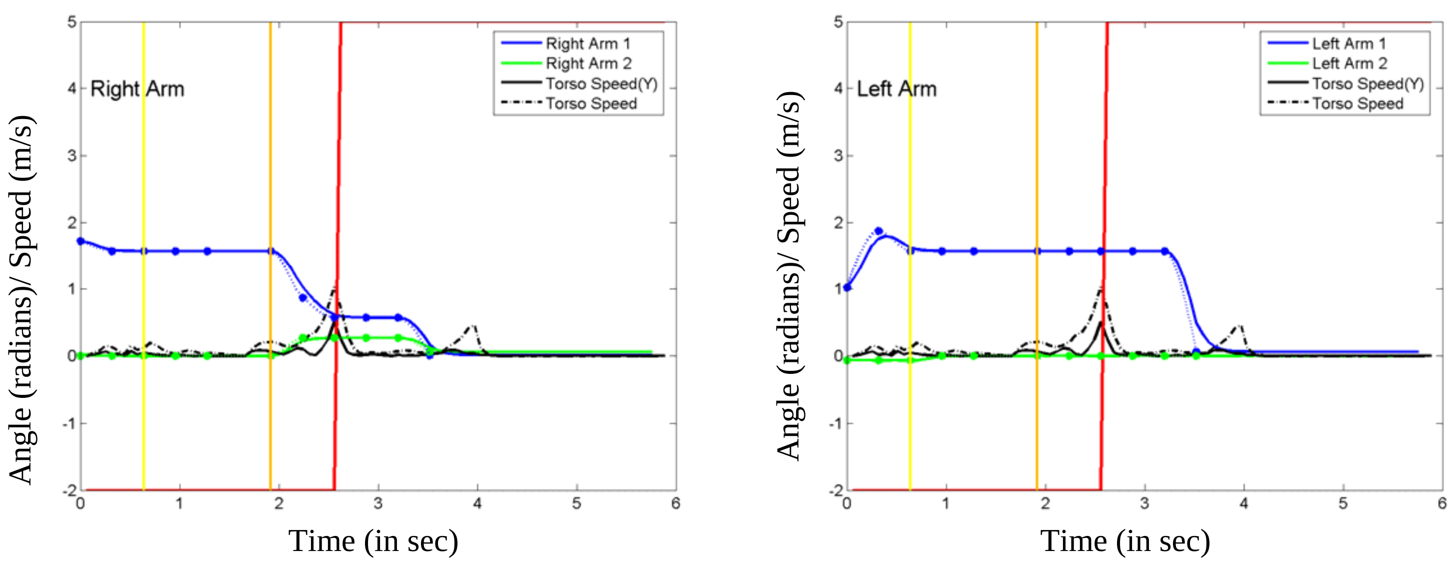
2.3.2 Robustness of sitting transition

The transition from crawling to sitting has to be robust to perturbation as robots deviate from the specified trajectories very often.

The robustness of the trajectory cannot be checked by just varying the points specified for the trajectory of a degree of freedom of the robot one at a time and seeing whether robot falls or not because trajectory points are interdependent. The robot may or may not fall for a given value of a trajectory point of a degree of freedom depending upon the values specified for the other trajectory points. Varying a trajectory point for all possible values of other trajectory points is not possible because the number of possible combinations grow exponentially with the number of trajectory points. Therefore we need to limit the trajectory points that we need to vary. The notion of *critical period* in the sitting transition defined in section 2.3.1 can be used for this purpose.

The robot is very stable in the first phase of the transition as one of its legs and both of its arms are touching the ground and center of mass is well inside the support polygon. Therefore we can check robustness of the trajectory only in the *critical period* when the robot is unstable. The degrees of freedom which move during the critical period are:
Right arm (Flexion / Extension and Abduction / Adduction)
Torso (Roll and Pitch)

To check the robustness of the sitting transition, I varied the trajectories of these DOFs (one at a time) in the critical period i.e. I varied the two specified trajectory points(Point no. 6 and 7, Figure 2.7(left)) that fall between orange and red line.



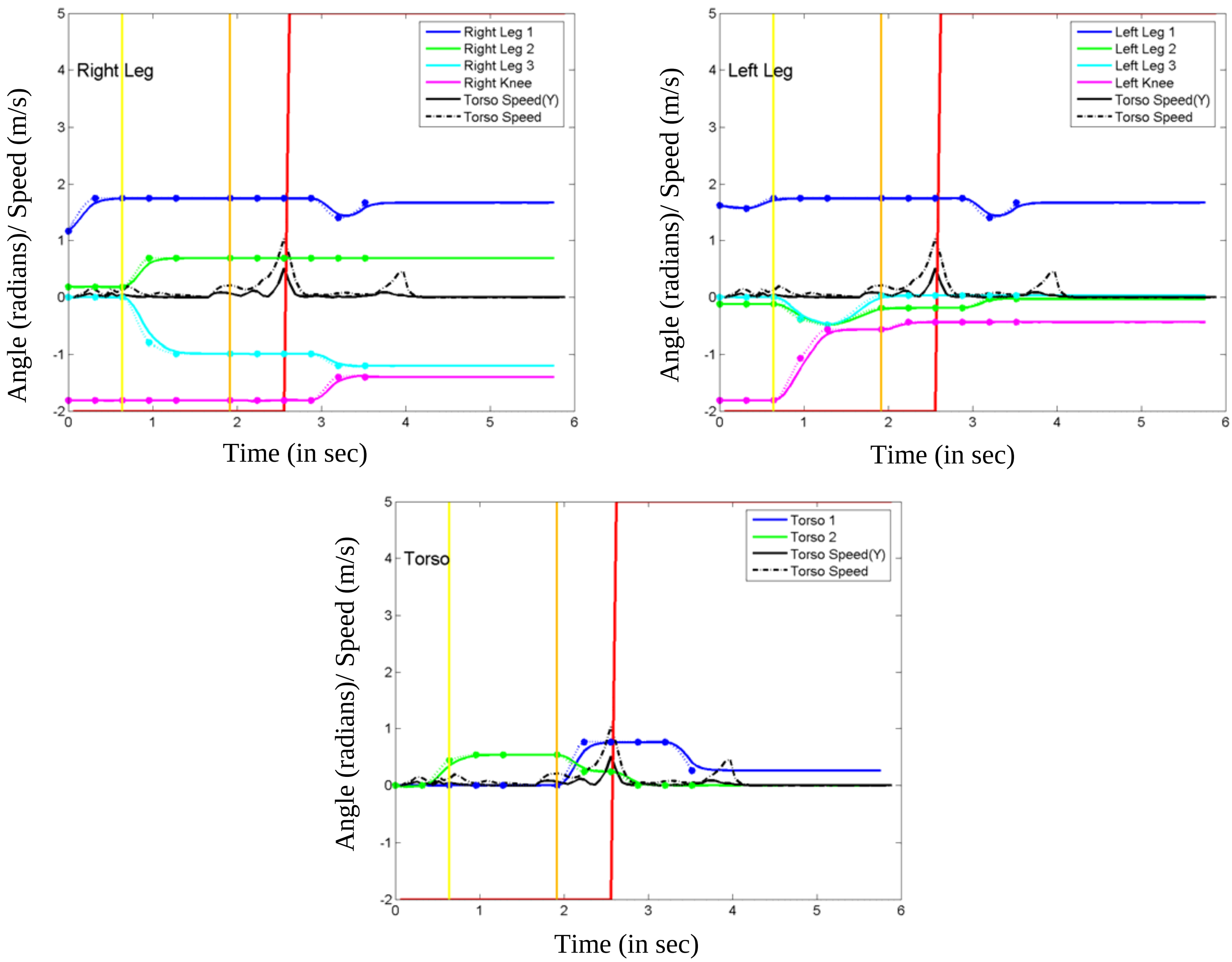


Figure 2.6: Variation of joint angles of relevant degrees of freedom and torso speed (vertical in solid black line and absolute in dotted black line) with time. (Top left) Variation of angles Right_arm_1 and Right_arm_2. (Top Right) Variation of angles Left_arm_1 and Left_arm_2. (Middle Left) Variation of angles Right_leg_1, Right_leg_2, Right_leg_3 and Right_knee. (Middle Right) Variation of angles Left_leg_1, Left_leg_2, Left_leg_3 and Left_knee. (Bottom) Variation of angles Torso_1 and Torso_2. The yellow vertical line (leftmost) is drawn at the time when robot starts moving its left leg. The orange vertical line (middle) is drawn at the time when robot has brought its left leg forward and starts moving its right arm. The red line (rightmost) is drawn at the time when robot sits on the ground. The names of the angles whose variations are plotted are defined in Figure 1.2.

The legs remain almost static during the critical period. Therefore, for right leg (Abduction / Adduction and Rotation) the constant value which these DOFs have during critical period is varied by varying Point no. 3 (Fig. 2.7 (right)) in the trajectory of right leg (Abduction/ adduction, angle name right_leg_2) and Point no. 4 (Fig. 2.7 (right)) in the trajectory of right leg (Rotation, angle name right_leg_3).

Other DOFs like right leg (Flexion /Extension), right knee, left leg (Flexion / Extension) and left knee have not been varied because by varying these DOFs, robot is able to sit but during transition there is lot of pressure on the ankles as knees do not touch the ground in most of the cases. The left leg (Abduction / Adduction and Rotation) have also not been varied because their value has to be near zero i.e. left leg has to come forward for the first phase to end, only then we can enter *critical period* by moving right arm backwards.

After the selection of the trajectory points that have to be varied, next important thing that needs to be determined is the detection of robot fall.
The robot is considered to have fallen when:

(i) the head of the robot touches the ground.

(ii) The angle of the line joining torso and head with the vertical axis is greater than 45° after the hips have touched the ground.

The second criterion is useful because sometimes robot does not fall with head touching the ground but is sitting in very unstable position from where a small perturbation may make the robot fall.

Figure 2.8-2.10 show the range of angles of the trajectory points over which robot does not fall for relevant DOFs. From Figure 2.8-2.10, we can observe **that there is a well defined and quite large region for all the DOFs in which robot is able to sit with stability. The specified points in the trajectory should lie in the center of that region so that sitting procedure is least affected by perturbations.**

This is true for the specified trajectory points of the hand made trajectory. In the next section, I will analyze the use of projection of center of mass as a criterion for deciding the stability of sitting transition.

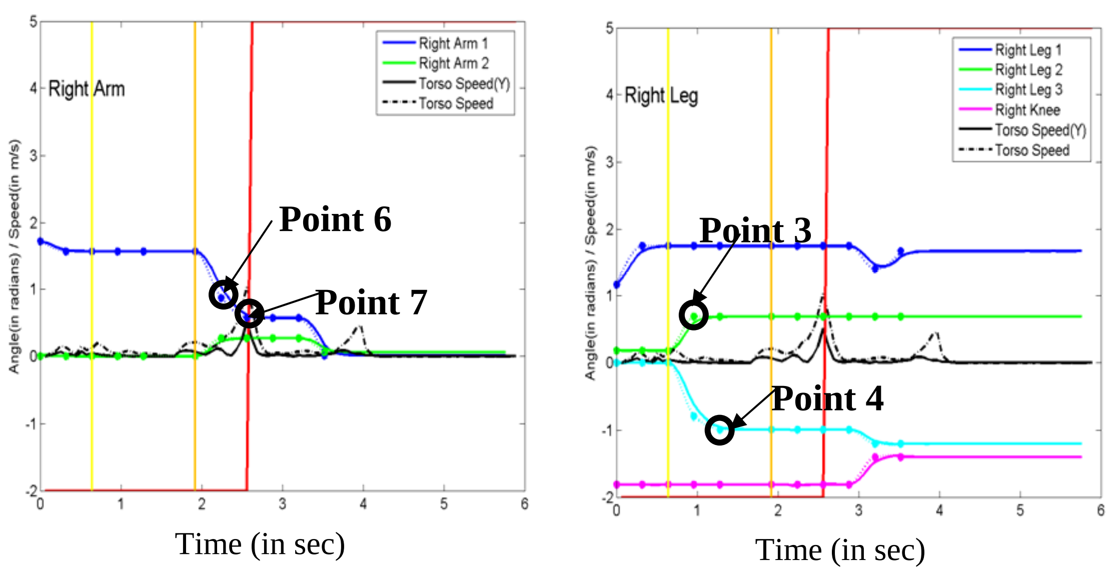


Figure 2.7: The points of trajectory that are varied

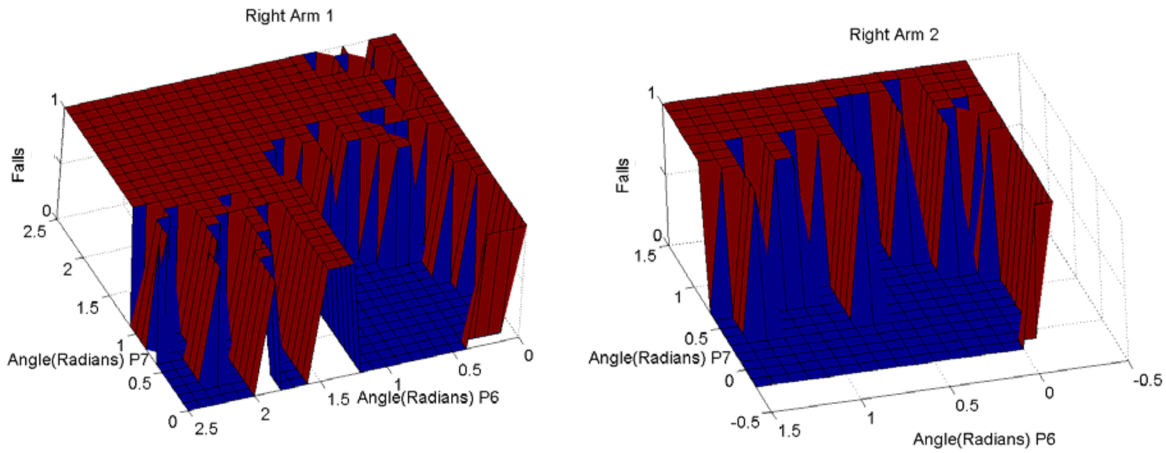


Figure 2.8: Falling behavior of robot on varying the points of trajectory specified for right arm in the critical region (left: right arm Flexion / Extension (angle name: right_arm_1), right: right arm Abduc / Adduc (angle name right_arm_2)) (Falls = 1 when robot falls)

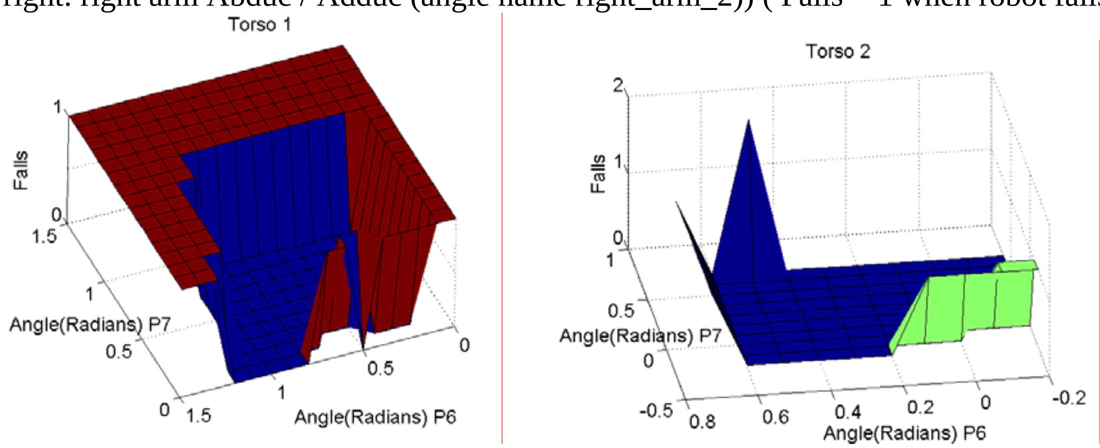


Figure 2.9: Falling behavior of robot on varying the points of trajectory specified for torso in the critical region (left : torso Roll (Angle name torso_1), right: torso Pitch (Angle name torso_2)) ((Falls > 0 when robot falls) For torso_2, when the robot falls on the head, “falls” has been given value 2 and when the sitting is not stable, “falls” has been given value 1.

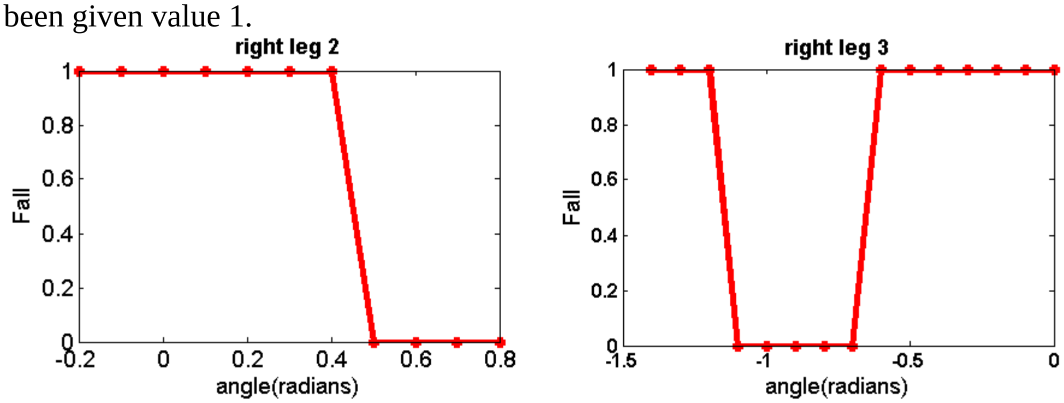


Figure 2.10: Falling behavior of robot on varying the constant value of trajectory specified for right leg in the critical region (Left: right leg Abduction / Adduction (angle name: right_leg_2), Right: Right leg Rotation (angle name: right_leg_3)) (Fall = 1 when robot falls)

2.3.3 Stability criterion based on center of mass

To classify which sitting transitions are good and which are bad, a criterion is needed to measure the stability of the sitting transition. The position projection of center of mass on the ground provides good information about the stability of the robot. If the projection of center of mass on the ground is outside the support polygon, the robot is unstable at that moment otherwise we can consider it stable when the speed of center of mass is not very high which is generally the case in sitting transition. Also if the distance of projection of center of mass from support polygon is larger, the instability is higher. Thus both the time for which center of mass is outside support polygon and the distance of center of mass from the support polygon, indicate the stability of the robot.

To capture both these quantities, I define stability measure as integration of distance of center of mass from support polygon with time during sitting. The distance of center of mass from support polygon is taken as perpendicular distance of center of mass from the closest edge of support polygon when center of mass is outside support polygon and zero when the center of mass is inside support polygon.

Figure 2.11-2.15 show the variation in this stability measure when the trajectory points of the degrees of freedom are varied like in Section 2.3.2. The stability measure has been named “CM Distance” in the plots.

As can be seen from the plots, the “CM Distance” cannot be used to distinguish between the regions of robot falling and not falling. This means that for sitting the center of mass always goes outside the support polygon. Also, there is not much variation in this quantity for the region in which robot does not fall. Therefore this criterion cannot be used to classify sitting transitions as good or bad.

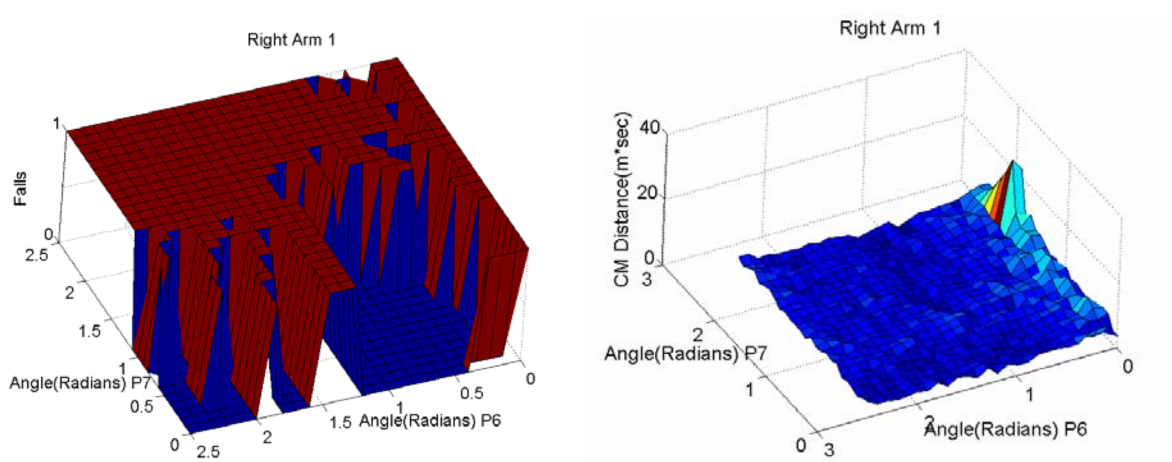


Figure 2.11: The left plot shows the region where robot falls (/ does not fall) and the right plot shows the variation in “CM_Distance” on varying the Points 6 and 7 of the trajectory of Right Arm Flexion / Extension.

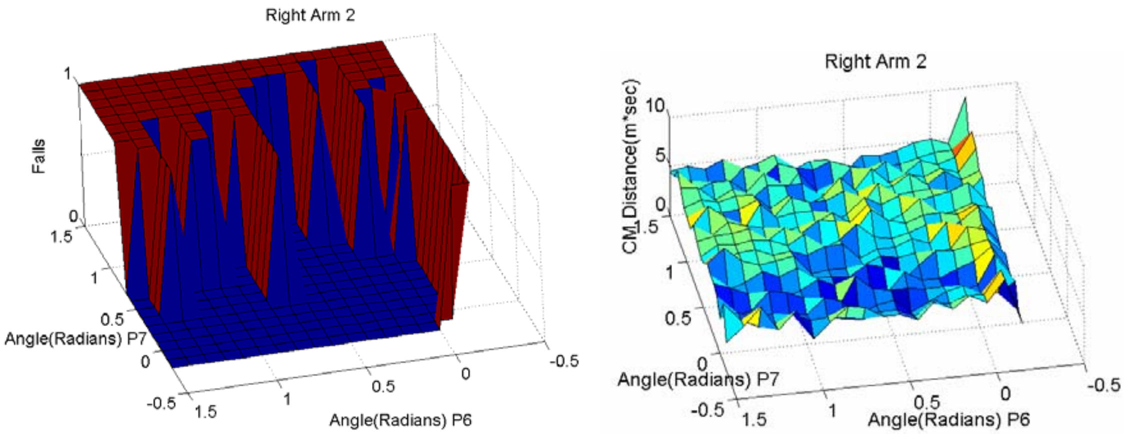


Figure 2.12: The left plot shows the region where robot falls (/ does not fall) and the right plot shows the variation in “CM_Distance” on varying the Points 6 and 7 of the trajectory of Right Arm Abduction / Adduction.

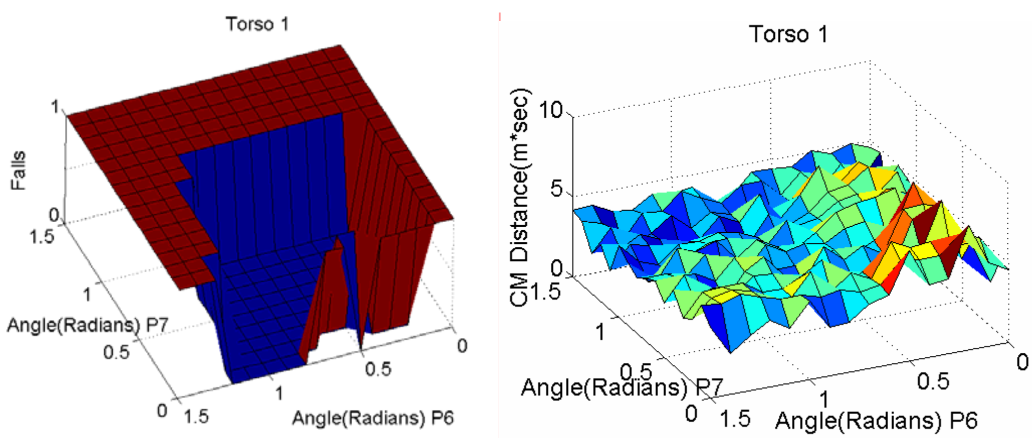


Figure 2.13: The left plot shows the region where robot falls (/ does not fall) and the right plot shows the variation in “CM_Distance” on varying the Points 6 and 7 of the trajectory of Torso Roll (angle name Torso 1).

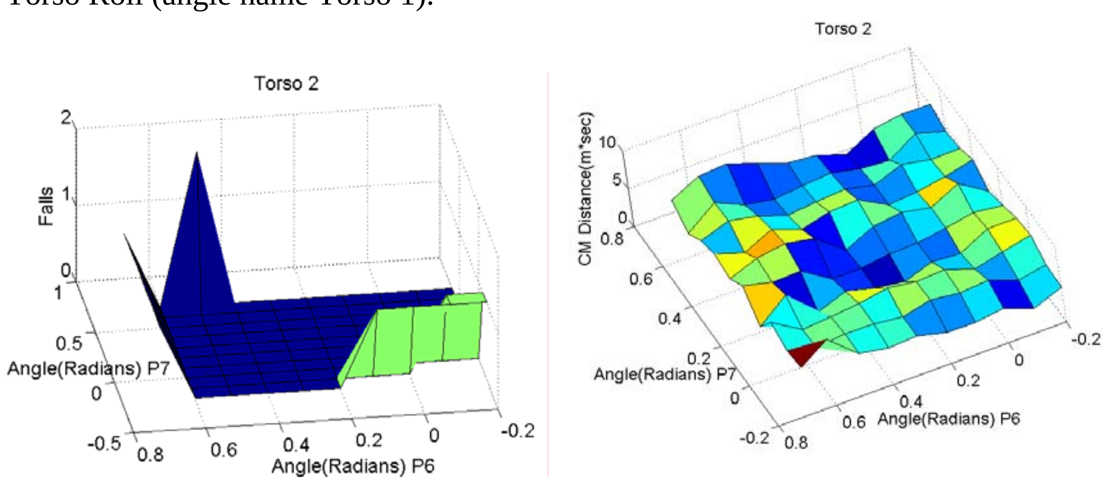


Figure 2.14: The left plot shows the region where robot falls (/ does not fall) and the right plot shows the variation in “CM_Distance” on varying the Points 6 and 7 of the trajectory of Torso Pitch (angle name Torso 2).

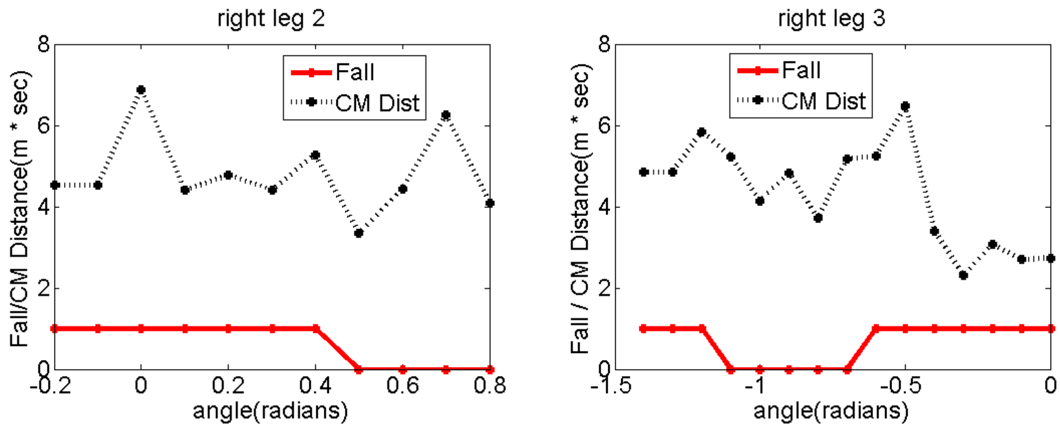


Figure 2.15: The "CM Distance" on varying Point 3 of the trajectory of Right Leg Abduction/ Adduction (angle name right leg 2) (left) and Point 4 of the trajectory of Right Leg Rotation (angle name right leg 3) (right) with the red line(bottom) showing the region in which robot falls / does not fall. The range for which the "fall" is zero is the range in which robot does not fall.

In the next section we will see whether it is necessary to attain a certain amount of torso speed for sitting or not.

2.3.4 Effect of speed of torso

If we see the variation of actual torso speed and vertical torso speed in trajectory plots of Figure 2.6, the torso speed starts building up from the start of orange line. There could be a possibility that if a minimum amount of torso speed it achieved at the start of the critical period, the robot will always sit. If this is the case then we can easily predict whether robot will sit or not at the start of the critical period.

To study the effect of speed of torso on the sitting of robot, I varied the time of moving right arm (Flexion /Extension) DOF from just 1 TimeStep (64 ms) to 60 Time Steps. This time is 5 Time Steps in the original trajectory.

By increasing the time of moving right arm (Flexion / Extension) DOF, torso speed can be decreased. Therefore we can study whether a minimum amount of torso speed is required to make robot sit or not. Figure 2.16 shows the torso speed profiles on varying the time of moving right arm (Flexion / Extension) DOF over (1, 2, 5, 10, 15, 30 and 60) Time Steps. Also for comparison, the torso speed profile for a trajectory when robot falls has been plotted in red color.

The robot was able to sit even when the time of moving right arm was 60 Time Steps. As can be seen in the plot, when the time of moving right arm is 60 Time Steps, torso speed starts building up from zero speed. Therefore we can infer that we need not achieve a minimum amount of torso speed for sitting.

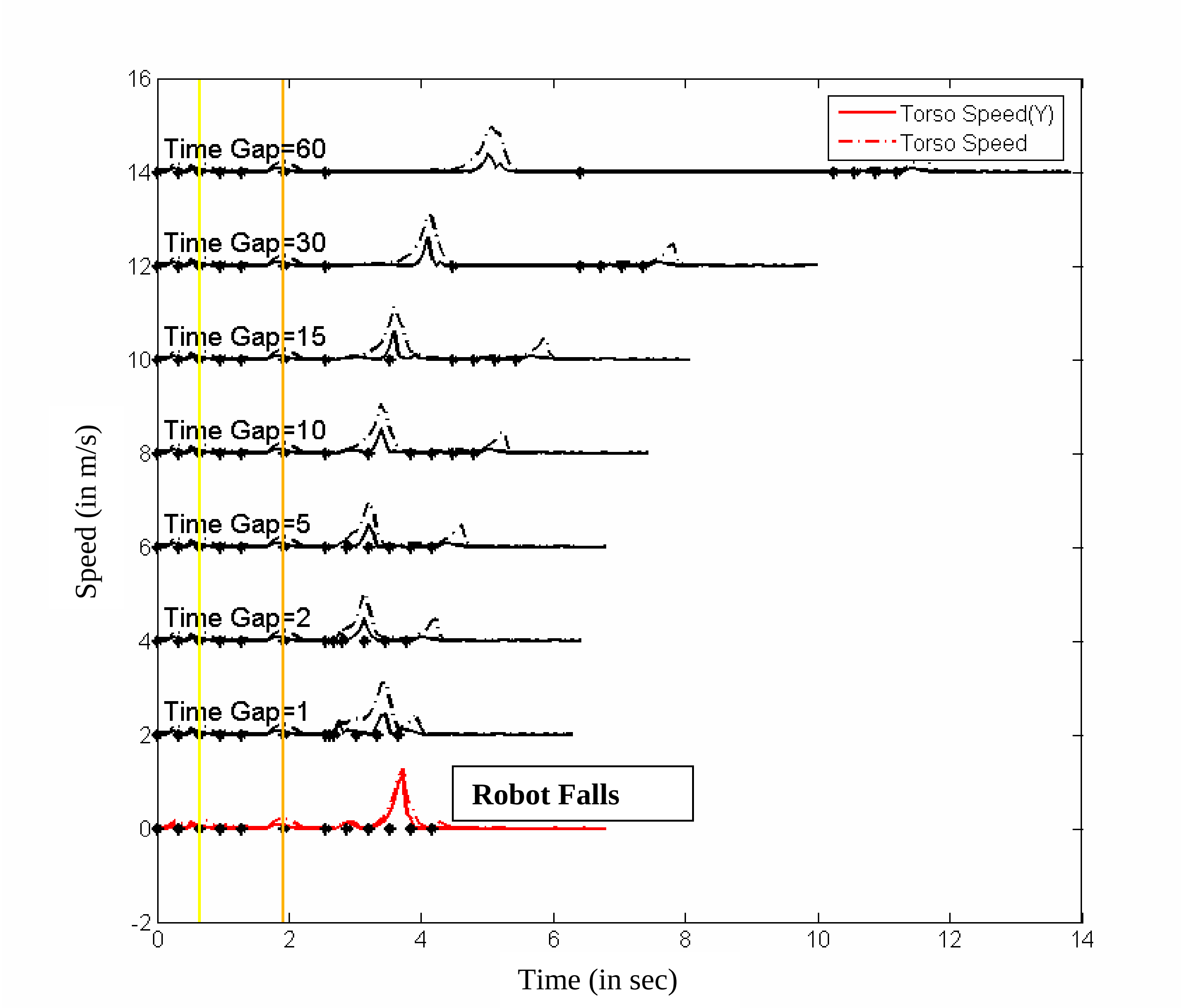


Figure 2.16: Torso Speed Profiles for different time steps of moving right_arm_1 in critical region. The red plot (bottom most) is the one when robot falls. Torso_1 is set to 0.16 radians for this plot.

2.3.5 Conclusion of analysis

From the analysis of the hand-made trajectory, following points can be noted:

(i) The sitting transition is divided into 2 phases.
(ii) The robot is unstable in the second phase.
(iii) The trajectory can be qualified as good or bad on the basis of its robustness.
(iv) From the position of center of mass we are not able to distinguish between the trajectories which make robot sit and which make robot fall. This means that during sitting robot always becomes unstable. Also there is not much variation in stability on the basis of position of center of mass.
(v) The torso speed cannot be used to predict the sitting of the robot. Infact, it was noticed that the trajectories in which arm does not loose the contact of the ground in the critical period, robot was able to sit.

Overall we can say that robustness is more important than the stability of the sitting transition and some amount of instability is required to make the robot sit. The robustness has been achieved in the current hand-made trajectory.

After the hand made trajectory has been analyzed and optimized, I will describe how we can make a dynamical controller for the trajectory.

Chapter 3

Dynamical System for Sitting

3.1 Need of Dynamical System and Main challenges

The controller based on dynamical system is advantageous because the trajectories can be easily modulated by controlling only a few parameters of dynamical system. In case of deviation from the trajectory, system smoothly returns to the trajectory and addition of sensory feedback can also be done very easily using the stability properties of the system.

To design the dynamical system for the controller of crawling to sitting transitions, two major problems need to be handled that are:

1) **Designing mathematical equations for sitting trajectories**
2) **Switching from crawling to sitting when a signal S is given**

By solving the first problem, we would be able to modulate sitting transition by using only few parameters and by solving the second problem we would be able to make robot sit whenever we wish to, by controlling a signal 'S'. In the next sections, I will describe the dynamical systems for the above two problems.

3.2 Mathematical model for sitting trajectories

The sitting transition is divided into two phases as explained above. Therefore, first we create a dynamical system for the first phase.

If we see the plots of variation of joint angles (Fig. 2.5), the degrees of freedom that move in the first phase are:

Torso Pitch (Angle name: Torso_2)
Right Leg Abduc / Adduc (Angle name: Right_leg_2)
Right Leg Rotation (Angle name: Right_leg_3)
Left Knee (Angle name: Left_Knee)
Left Leg Abduc / Adduc (Angle name: Left_leg_2)
Left Leg Rotation (Angle name: Left_leg_3)

Also the degrees of freedom like:

Right Arm Flex/Ext (Angle name: Right_Arm_1)
Right Arm Abduc /Adduc (Angle name: Right_Arm_2)
Right Elbow (Angle name: Right_elbow)

Left Arm Flex / Ext (Angle name : Left_arm_1)
Left Arm Abduc /Adduc (Angle name: Left_arm_2)
Left Elbow (Angle name: Left_elbow)
Right Leg Flex / Ext (Angle name: Right_leg_1)
Left Leg Flex /Ext (Angle name; Left_leg_1)

that were moving while crawling become constant while sitting. The equation for the degrees of freedom that were moving while crawling using x_d to denote the value of angle named '*d*' can be written as follows:

$$\dot{x}_d = y_d$$

$$\dot{y}_d = \alpha_d \cdot (x_d - x0_d) + \beta_d \cdot y_d \qquad \text{Eq(1)}$$

where d can be right_arm_1, right_arm_2, right_elbow, left_arm_1, left_arm_2, left_elbow, right_leg_1, left_leg_1

α_d and β_d are constants whose values are same for all the DOFs

$x0_d$ is the constant value of the angle named 'd' during first phase

Among the degrees of freedom that start moving during the first phase of sitting, first Torso Pitch starts moving as described in section 2.2. The equation for the movement of torso pitch using x_{torso_2} to denote the value of angle torso_2, can be written as follows:

$$\dot{x}_{torso\_2} = y_{torso\_2}$$

$$\dot{y}_{torso\_2} = \alpha_{torso\_2} \cdot (x_{torso\_2} - x0_{torso\_2}) + \beta_{torso\_2} \cdot y_{torso\_2} \qquad \text{Eq(2)}$$

$$\beta_{torso\_2} = -160$$

$$\alpha_{torso\_2} = -\beta_{torso\_2} * \beta_{torso\_2} / 32$$

With this equation the angle torso_2 will move towards $x0_{torso\_2}$ which is the behavior we wish to have. The speed of the movement can be controlled by α_{torso_2} and β_{torso_2}.

Then the movement of right leg and left leg is started. The equation for the movement of right leg and left knee can be written in the same way as for torso pitch with an additional factor that ensures that right leg and left knee start moving only after torso has started moving. The equations are as follows:

$$\dot{x}_d = T * (y_d)$$

$$\dot{y}_d = T * (\alpha_d \cdot (x_d - x0_d) + \beta_d \cdot y_d) \qquad \text{Eq(3)}$$

$$T = \frac{1}{1 + e^{-100*(x_{torso\_2} - 0.8*x0_{torso\_2})}}$$

$$where \quad d\ can\ be\ right\_leg\_2, right\_leg\_3, left\_knee$$
$$\alpha_{right\_leg\_2} = \alpha_{torso\_2} \quad \beta_{right\_leg\_2} = \beta_{torso\_2}/2$$
$$\alpha_{right\_leg\_3} = \alpha_{torso\_2}/2 \quad \beta_{right\_leg\_3} = \beta_{torso\_2}/2$$
$$\alpha_{left\_knee} = \alpha_{torso\_2}/2 \quad \beta_{left\_knee} = \beta_{torso\_2}/2$$

The value of T will be very small until the value of angle torso_2 is not 0.8* $x0_{torso\_2}$ **. Thus right leg and left knee will not move until the value of angle torso_2 is 0.8*** $x0_{torso\_2}$ **. This ensures that when right leg and left knee start moving, weight of the body is supported mostly by right half of the body. The T can also be multiplied by an external sensory signal which makes T approach 1 only when the body weight is supported by right half of the body.**

Also as explained in section 2.2, the movement of left leg (Abduc/Adduc and Rotation) has to be synchronized with the movement of left knee. This is done using the following equations:

$$\dot{x}_d = T * (K \cdot c_1 \cdot x_d \quad + \quad c_2 \cdot (x_{left\_knee} - x0_{left\_knee}) \cdot (x_d - x0_d))$$
$$where\ T\ is\ the\ same\ as\ in\ Eq(2)$$
$$K = \frac{1}{1 + e^{100 * y_{left\_knee} * y_{left\_knee}}}$$
$$d\ can\ be\ left\_leg\_3, left\_leg\_2 \qquad \text{Eq(4)}$$
$$c_1 = \beta_{left\_knee}/10$$
$$c_2 = 8$$

When the left knee is extending, value of K is very small. Therefore the second half of the equation will make x_d decrease until either left knee stops extending or x_d becomes equal to $x0_d$. When the extension of left knee will complete, second half of the equation will become zero as x_{left_knee} will become equal to $x0_{left\_knee}$, first half will become active as y_{left_knee} will become zero and will move x_d to zero. This completes the first phase of the sitting transition.

The degrees of freedom that move in the second phase are:

Torso Pitch (Angle name: torso_2)
Torso Roll (Angle name: torso_1)
Right Arm Flex. / Ext. (Angle name: right_arm_1)
Right Arm Abduc / Addduc (Angle name: right_arm_2)

The degree of freedom Torso Roll was not moving during crawling or during the first phase of sitting. Therefore its equation can be written as:

$$\dot{x}_{torso\_1} = P * (y_{torso\_1})$$

$$\dot{y}_{torso\_1} = P * (\alpha_{torso\_1} \cdot (x_{torso\_1} - x0_{torso\_1}) + \beta_{torso\_1} \cdot y_{torso\_1})$$

$$\alpha_{rtorso\_1} = \alpha_{torso\_2} / 2 \quad \beta_{torso\_1} = \beta_{torso\_2} / 4 \qquad \text{Eq(5)}$$

$$P = \frac{e^{1000*(P1-0.2)}}{1 + e^{1000*(P1-0.2)}}$$

$$P1 = \frac{1}{1 + e^{100*(x_{left\_leg\_3})*(x_{left\_leg\_3})}} \cdot \frac{1}{1 + e^{100*(x_{left\_knee} - x0_{left\_knee})*(x_{left\_knee} - x0_{left\_knee})}}$$

The value of P will be very small during the first phase of sitting and will become 1 when the first phase will end i.e when left leg (Rotation) becomes zero and extension of left knee is complete. Like variable T, variable P can also be multiplied by external sensory signal by which we can control the start of the critical phase of sitting. The DOF Torso Roll will start moving only when the first phase will end and P will become 1.

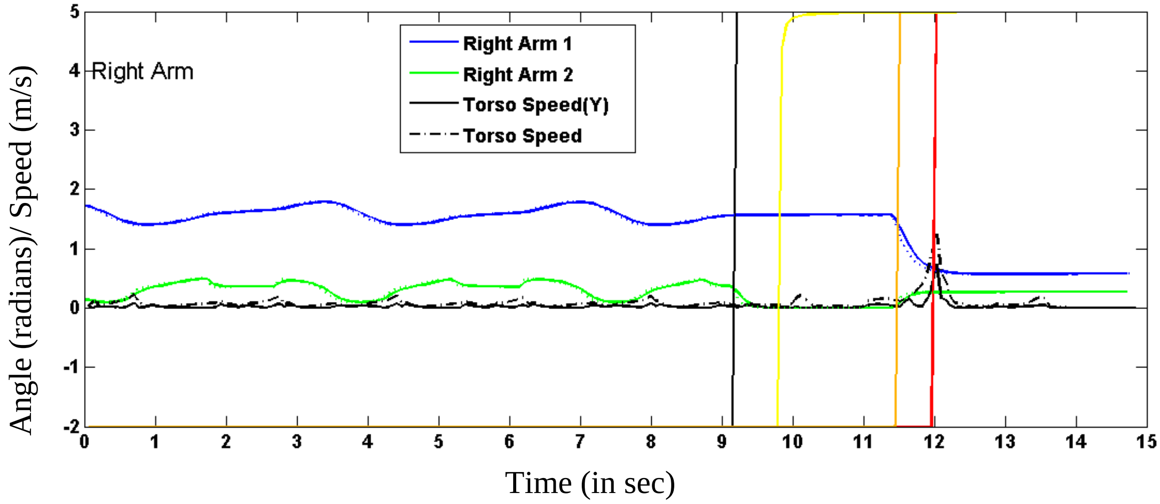
The equations of degrees of freedom Torso Pitch, Right Arm Flex/Ext and Right Arm Abduc/Adduc that were moving before also can be modified by replacing

$x0_d$ with $(x0_d + P * (x1_d - x0_d))$.

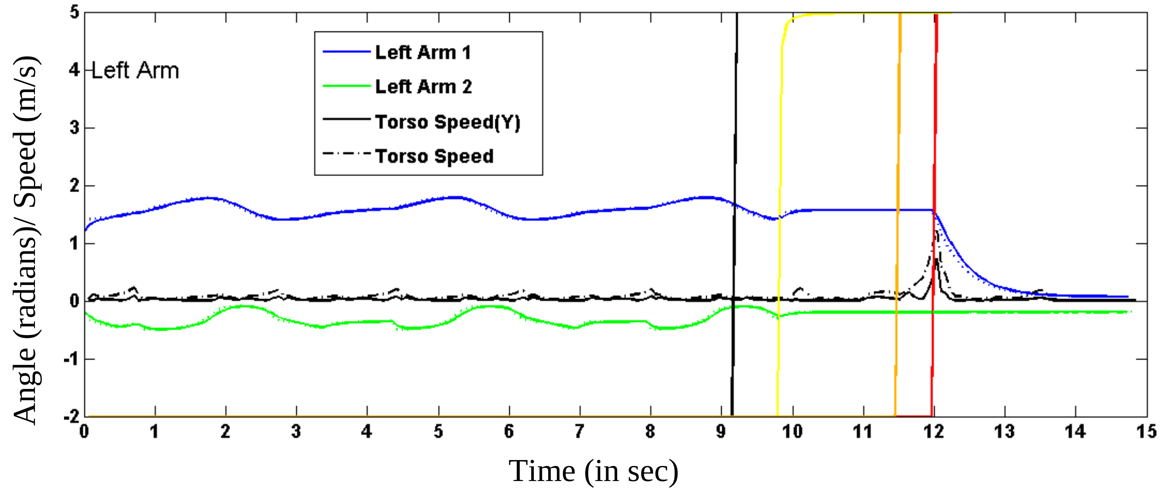
This will make these degrees of freedom move towards $x1_d$ when the second phase of sitting transition will start. Similarly, when sitting is over i.e. hips touch the ground, we can change the attractor of left arm (Abduction / Adduction) and right leg (Rotation) to make the sitting pose stable.

The trajectories for relevant DOFs obtained using above equations are shown in figure 3.1. As before, the robot starts sitting after yellow line (second vertical line from the left), the orange line (third vertical line from left) marks the end of first phase i.e $P = 1$ at this point. The red line (right most vertical line) is drawn when robot sits. Before the yellow line (second vertical line from the left), robot is crawling and the black line (leftmost vertical line) is drawn at the time when signal for sitting is sent. The switching from crawling to sitting has been explained in the next section.

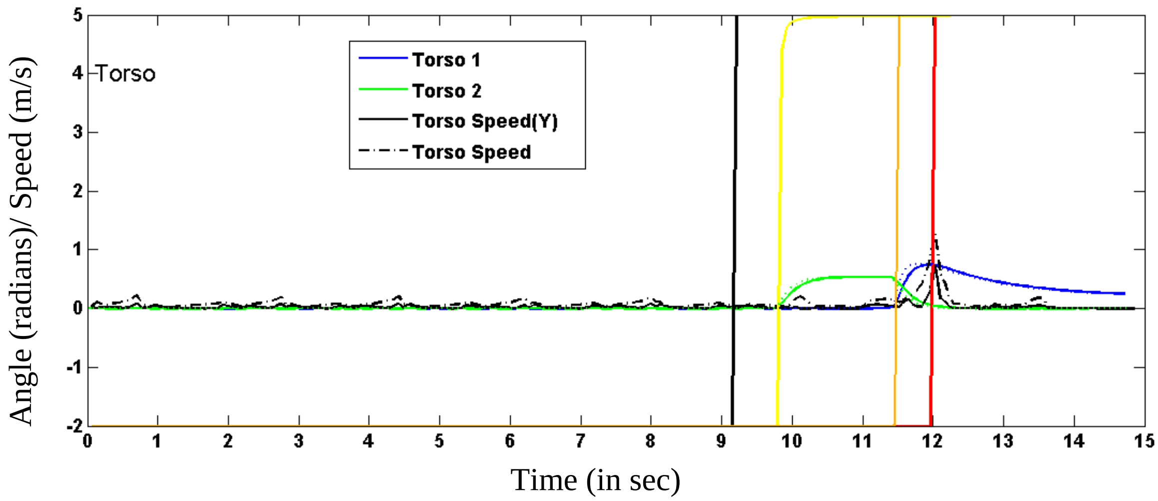
From the plots we can notice, that the trajectories similar to hand made trajectories have been obtained until the red line (right most vertical line). The trajectory after this line only helps the robot sit in a proper position. So the trajectories need not be same as hand made trajectory after red line (right most vertical line).



Right Arm
Right Arm 1
Right Arm 2
Torso Speed(Y)
Torso Speed
Angle (radians)/ Speed (m/s)
Time (in sec)



Left Arm
Left Arm 1
Left Arm 2
Torso Speed(Y)
Torso Speed
Angle (radians)/ Speed (m/s)
Time (in sec)



Torso
Torso 1
Torso 2
Torso Speed(Y)
Torso Speed
Angle (radians)/ Speed (m/s)
Time (in sec)

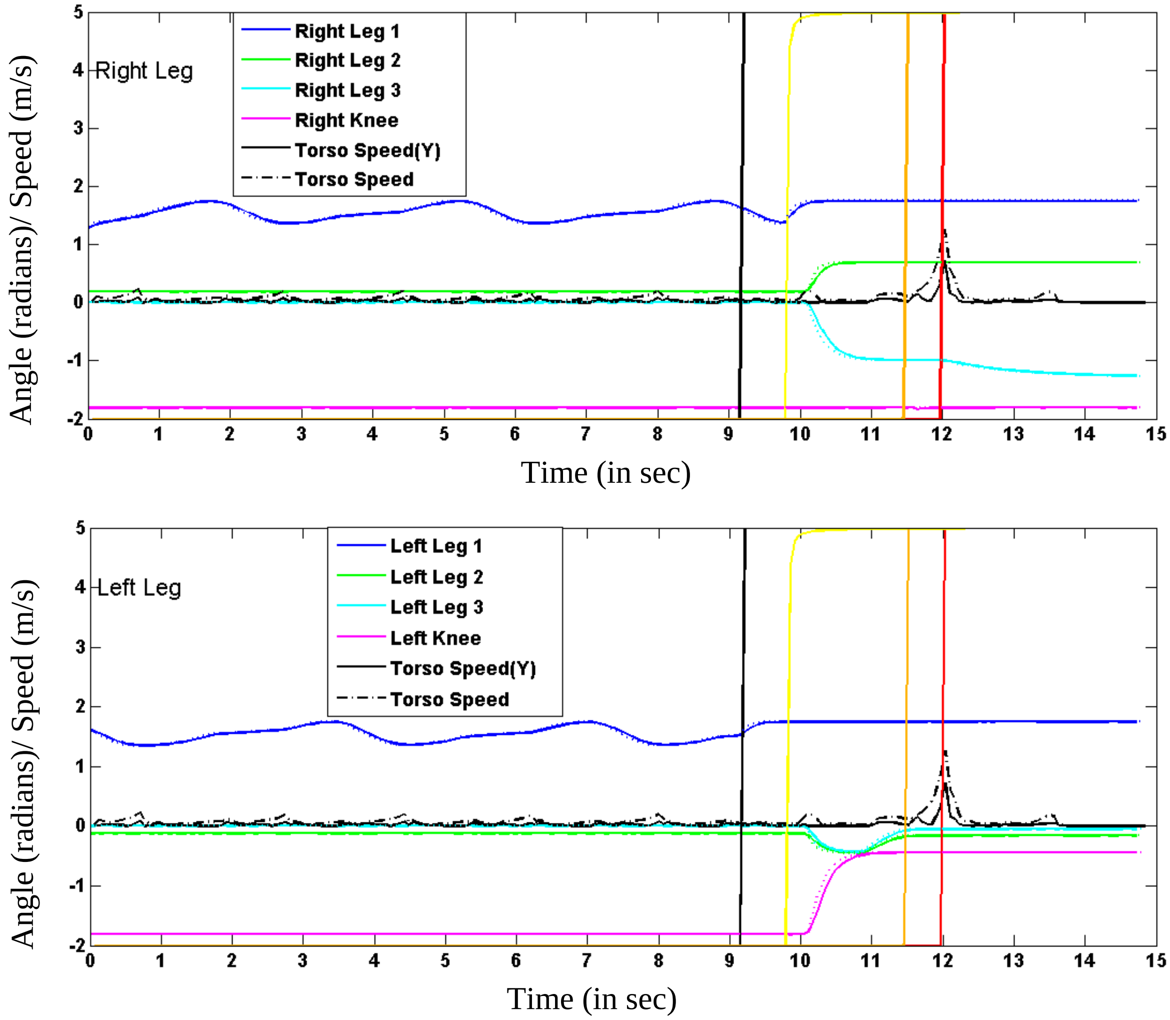


Figure 3.1: Variation of joint angles of relevant degrees of freedom and torso speed (vertical in solid black line and absolute in dotted black line) with time. (Top) Variation of angles Right_arm_1 and Right_arm_2. (Second from Top) Variation of angles Left_arm_1 and Left_arm_2. . (Third from Top) Variation of angles Torso_1 and Torso_2. (Fourth from Top) Variation of angles Right_leg_1, Right_leg_2, Right_leg_3 and Right_knee. (Bottom) Variation of angles Left_leg_1, Left_leg_2, Left_leg_3 and Left_knee. Till black line (leftmost vertical line) robot is crawling. Then it gets signal for sitting at black line. At yellow vertical line (second from left) robot starts sitting by moving its torso first. The orange vertical line(second from left) is drawn at the time when robot has brought its left leg forward and starts moving its right arm. The red line(right most) is drawn at the time when robot sits on the ground. The names of the angles whose variations are plotted are defined in Figure 1.2.

In the next section I will describe how we can smoothly switch from crawling to sitting.

3.3 Switching from crawling to sitting

While crawling, infants have a trot like gait, which is a periodic gait. The equations of the CPG that generates the trajectories for the hip and shoulder joints for crawling as described in [2] are:

$$\dot{x}_i = y_i$$

$$\dot{y}_i = \alpha_i y_i (K_i(\mu^2 - x_i^2) - y_i^2) - K_i x_i - c_1 y_j + c_2 y_k$$

$$K_i = \frac{k_{stance}}{(e^{-by_i}+1)(e^{-ky_j}+1)} + \frac{k_{swing}}{(e^{by_i}+1)} \qquad \text{Eq(6)}$$

$$\alpha_i = \nu(1 + \beta e^{-\sigma x_i^2})$$

where i = 1 …4 denotes the ith oscillator, j the opposite oscillator and k the diagonal oscillator, c_1 and c_2 are positive coupling constants for the CPG architecture shown in figure 3.2 below.

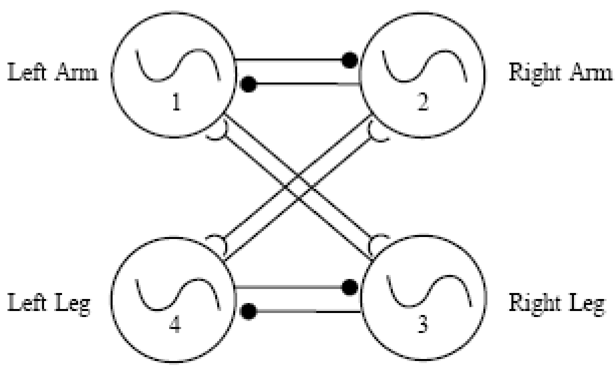


Figure 3.2: The architecture of CPG (Source [2])

We want when we switch S from 0 to 1, we should get sitting controller. For this, we can get a combined signal from the oscillator as well as from the dynamical system for sitting and use the signal S to shut off the oscillator or the dynamical system for sitting by modifying their equations as shown below:

For oscillator

$$\dot{ox}_d = (1-S)\cdot f_{d1}(\vec{ox}, \vec{oy})$$

$$\dot{oy}_d = (1-S)\cdot f_{d2}(\vec{ox}, \vec{oy})$$

For Dynamical System

$$\dot{dsx}_d = S\cdot f_{d3}(\vec{dsx}, \vec{dsy})$$

$$\dot{dsy}_d = S\cdot f_{d4}(\vec{dsx}, \vec{dsy})$$

Combined Signal $cx_d = ox_d + dsx_d$ Eq(7)

The problem with this equation is that the controller will shift abruptly from crawling to sitting on switching S from 0 to 1. By abruptness I mean that even if the leg is moving backward, it will immediately start moving forwards without completing its cycle as shown in Figure 3.3. This will require large amount of acceleration. Therefore we wish that after the signal S is changed from 0 to 1, switching from crawling to sitting controller should occur only when while crawling hip and shoulder joints are moving in the same direction as they will move after shifting from crawling to sitting. During sitting, hip and shoulder joints are extended to large extent, therefore it is desirable that switching from crawling to sitting takes place when hip and shoulder joints start extending. This can be achieved by substituting S by S_i' defined as:

$$S_i' = S.\frac{1}{1+e^{-D*osy_i}}$$

S_i' will become 1 only when S is 1 and osy_i is positive i.e osx_i is increasing. For the degrees of freedom related to Left Arm, S will be substituted by S_1', for Right Arm by S_2', for Right Leg by S_3' and for left leg by S_4'. For Torso, S is substituted by S_3' as movement of torso results in increased pressure on right leg. The effect of this substitution is shown in the figure 3.3 below. Also in Fig. 3.1, the black line (left most vertical line) corresponds to signal S and yellow line (second vertical line from left) corresponds to signal S_3'. Figure 3.4 shows snapshots of the robot switching from crawling to sitting when following the trajectories shown in Fig 3.1.

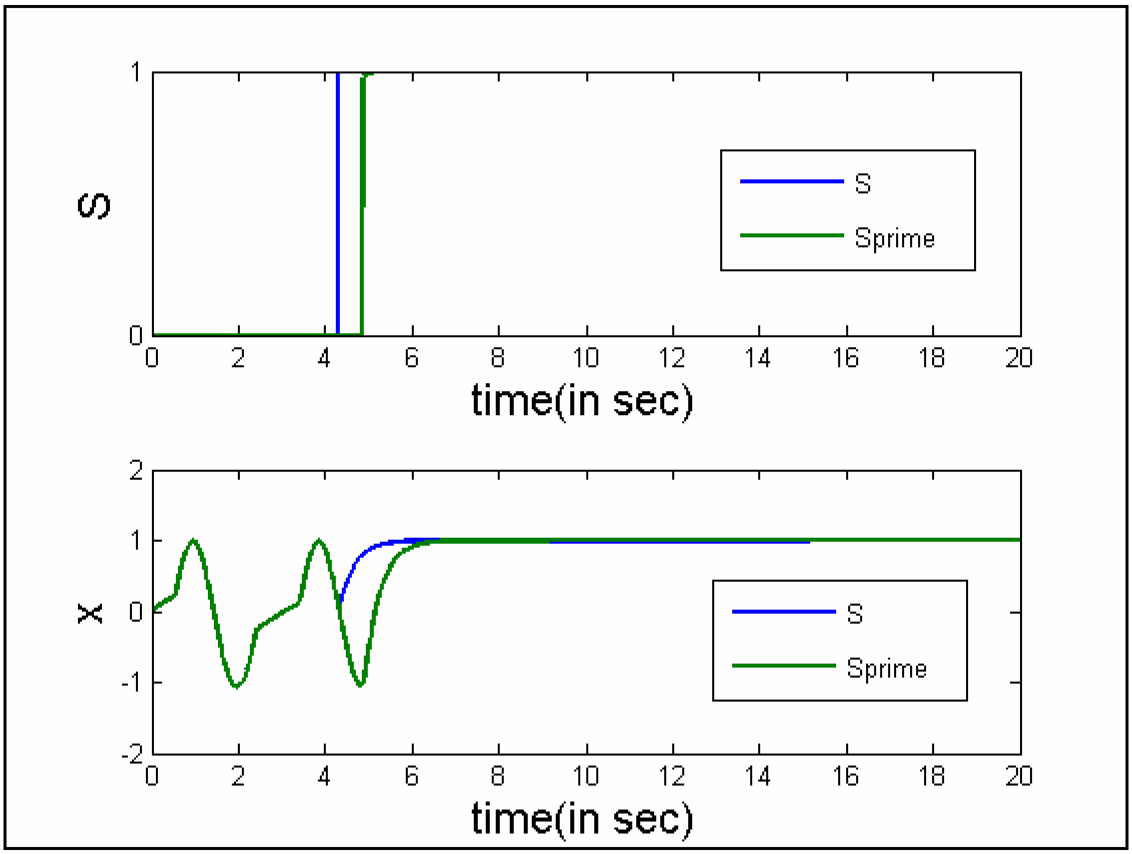


Figure 3.3: Switching from crawling to sitting. Effect of replacing switching signal S by S'

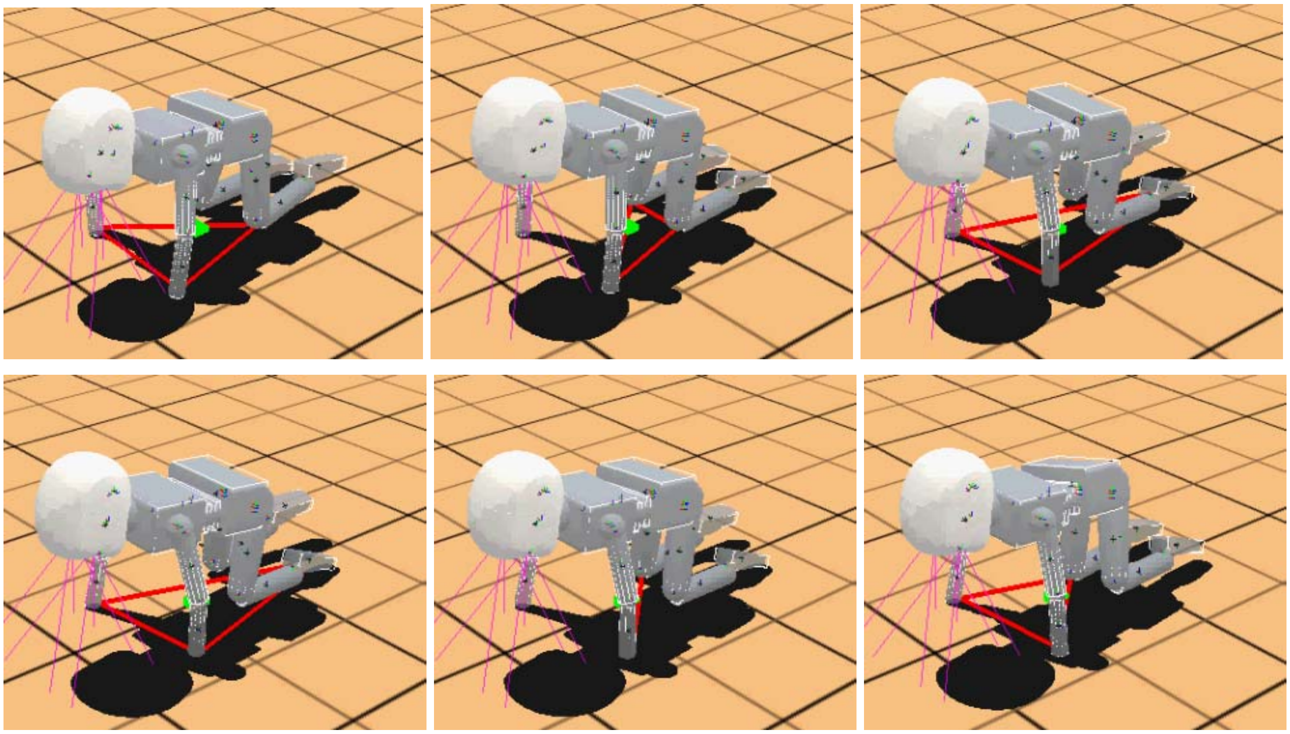


Figure 3.4: Robot switching from crawling to sitting. In the first 3 snapshots, robot is crawling. The signal for sitting is given at the time of third snapshot but torso starts moving only by 6th snapshot as right leg is going backwards in third snapshot. Left leg and arms become constant after third snapshot. The snapshots have been taken from video: Craling_2_sitting_right

Thus smooth switching from crawling to sitting oscillator is achieved.

Conclusion and Future Work

A controller for sitting of the robot in the same way as infants has been successfully implemented. The sensory feedback can easily be integrated into this controller by modifying the values of variable T (defined in Eq(3)) and P (defined in Eq(5)) according to the sensory input.

The robot can be switched from crawling to sitting smoothly at anytime by providing an external signal S.

Also the main characteristics of the sitting behavior of infants and the period of instability have been identified.

The future work that can be done is:

1) Addition of sensory feedback while sitting. This will be particularly useful when robot is in critical period. It was observed that robot falls in the critical period when arm looses contact of the ground. Sensory feedback might be very helpful in preventing the fall.

2) Collection of biological data to know that when infants enter the critical period of sitting phase, their movements are controlled by signals from brain or signals from spinal cord.
3) Development of controller for transition from sitting to crawling
4) Increase in the limit up to which hip joints can be flexed / extended.

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