Learning Motion Dynamics to Catch a flying object

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Goal

Catching a moving object on the fly.

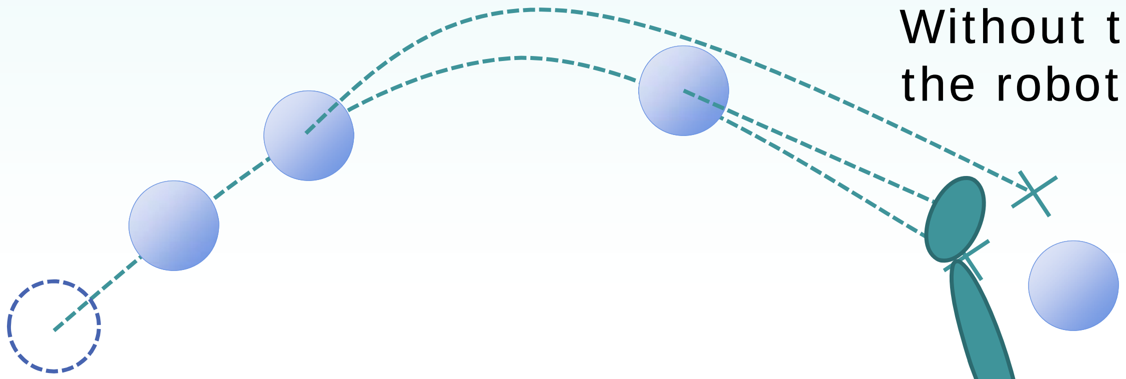
[1] http://web.mit.edu/nsl/www/

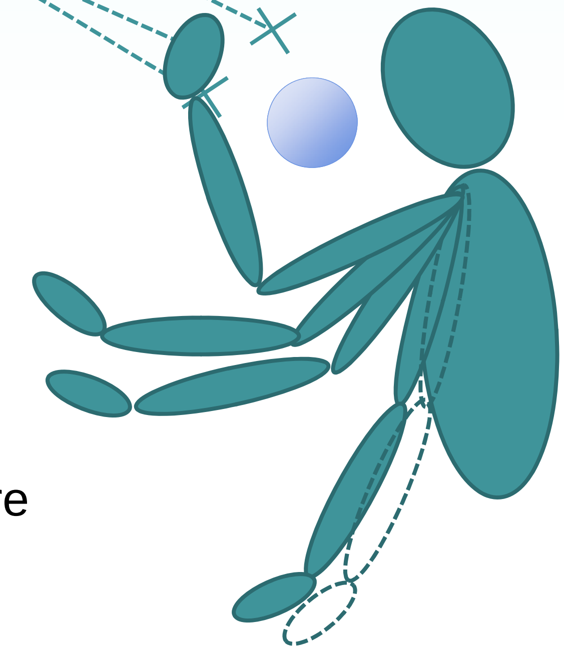
[1] Hong & Slotine,1995 ISER

Challenges

1. Quickly-adapt the planned trajectory so as to catch the object, when receiving more accurate estimate of the object's motion.
2. Motion timing control to synchronize the robot's movements with the dynamics of a moving object.

Without timing control,
the robot fails to catch the ball





Imprecise estimation of the ball motion
(inaccuracy of vision)

→ **Re-plan on the fly** arm trajectory, to more accurate estimation of the target position.

Related Works

- Trajectory generation to catch a moving object using Polynomials [1][2][3]

- Trajectory generation to catch a moving object using Motion Primitives generated by Programmable Pattern Generators (PPGs) [4]

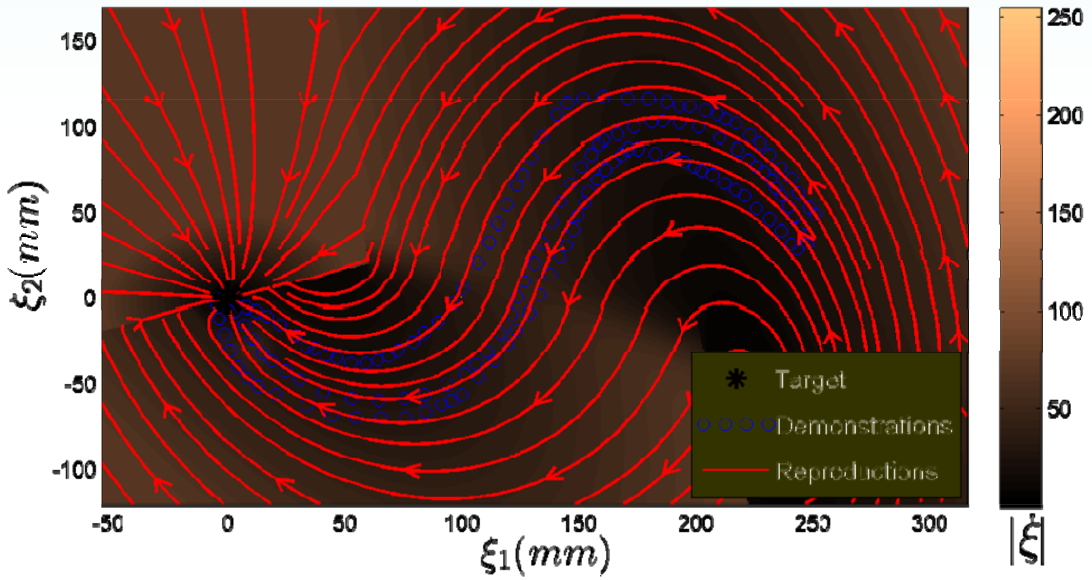
[1] Hong & Slotine,1995 ISER
[2] Zhang et al.,1994 ISIC
[3] Namiki et al., 2003 ICRA
[4] Riley et al. 2002 Autonomous Robots

Learning Nonlinear Motion Dynamics

A motion representation is learned as ***a first order autonomous dynamical system*** [6] [7]

$$\dot{\xi} = f(\xi)$$

We use human demonstrations and construct f such that it produces motions similar to those demonstrated.



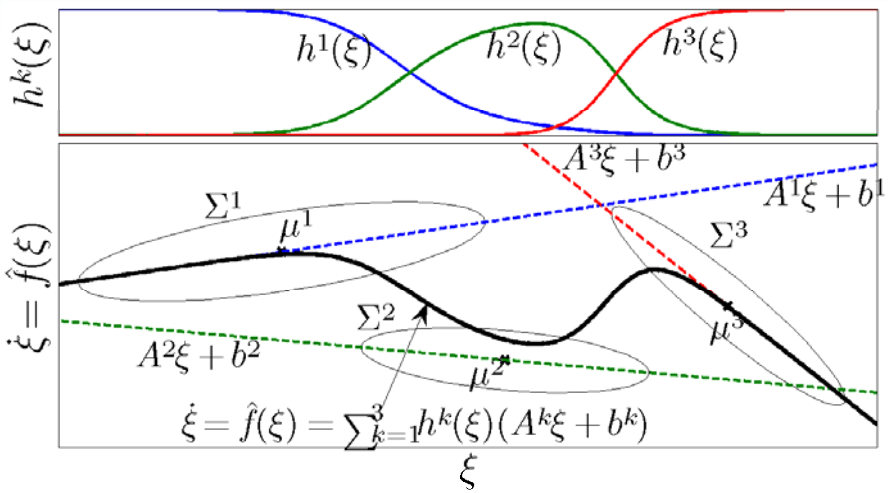
[6] S.M. Khansari-Zadeh and Billard, ICRA 2010

Learning Nonlinear Motion Dynamics

We use a probabilistic approach and model the function f using Gaussian Mixture Models (GMM) and can be retrieved using Gaussian Mixture Regression (GMR):

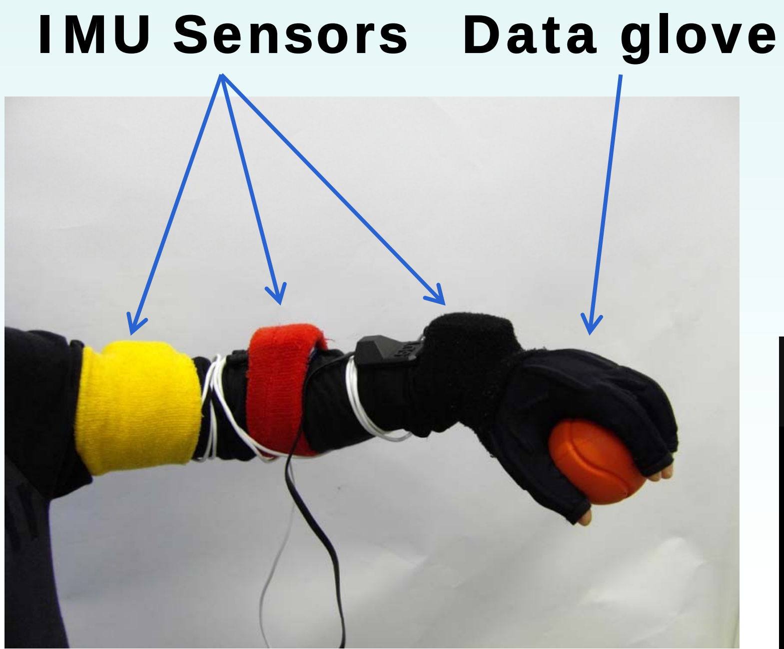
$$\hat{\dot{\xi}} = \hat{f}(\xi;\theta) = \sum_{k=1}^{K} h^k(\xi)(A^k\xi + b^k) = \sum_{k=1}^{K} h^k(\xi)\left(\Sigma^k_{\dot{\xi}\xi}(\Sigma^k_{\xi})^{-1}\xi + (\dot{\mu}^k_{\dot{\xi}} - \Sigma^k_{\dot{\xi}\xi}(\Sigma^k_{\xi})^{-1}\mu^k_{\xi})\right)$$

μ^k and Σ^k, $k = 1..K$ are the means and covariance matrices of the K Gaussian distributions



Further information on how the parameters of the motion are learnt in ICRA 2010: Khansari-Zadeh and Billard, 09:00-09:15, Paper WeA7.3

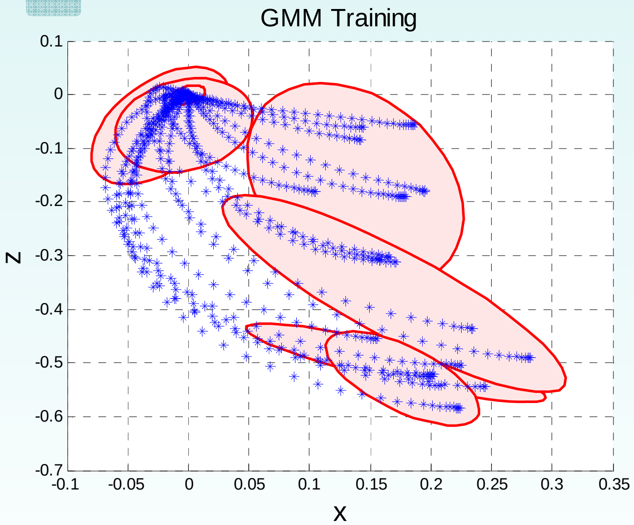
Human demonstrations

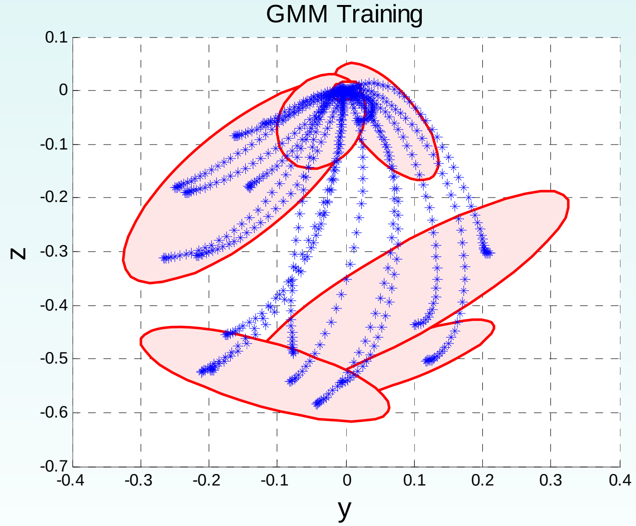


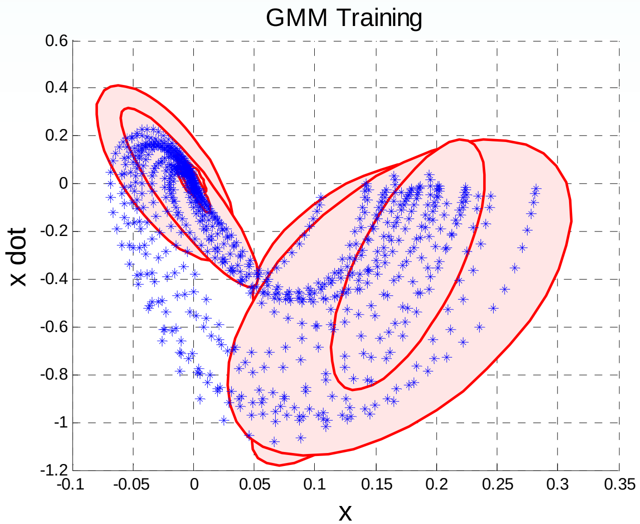
< motion capture system >

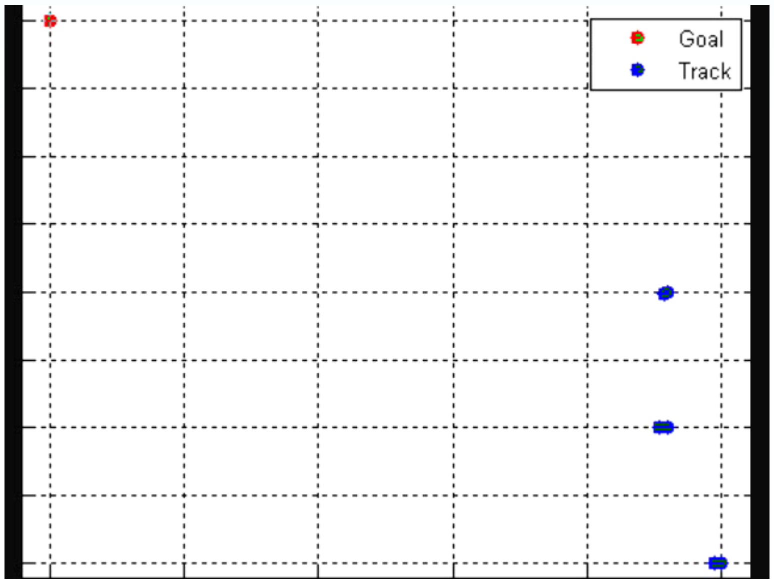
Motions
- Capturing rate is around 15 Hz
- 0.8~1.2 sec for each demonstration
- 20 demonstrations

Learning Nonlinear Motion Dynamics









Timing Control

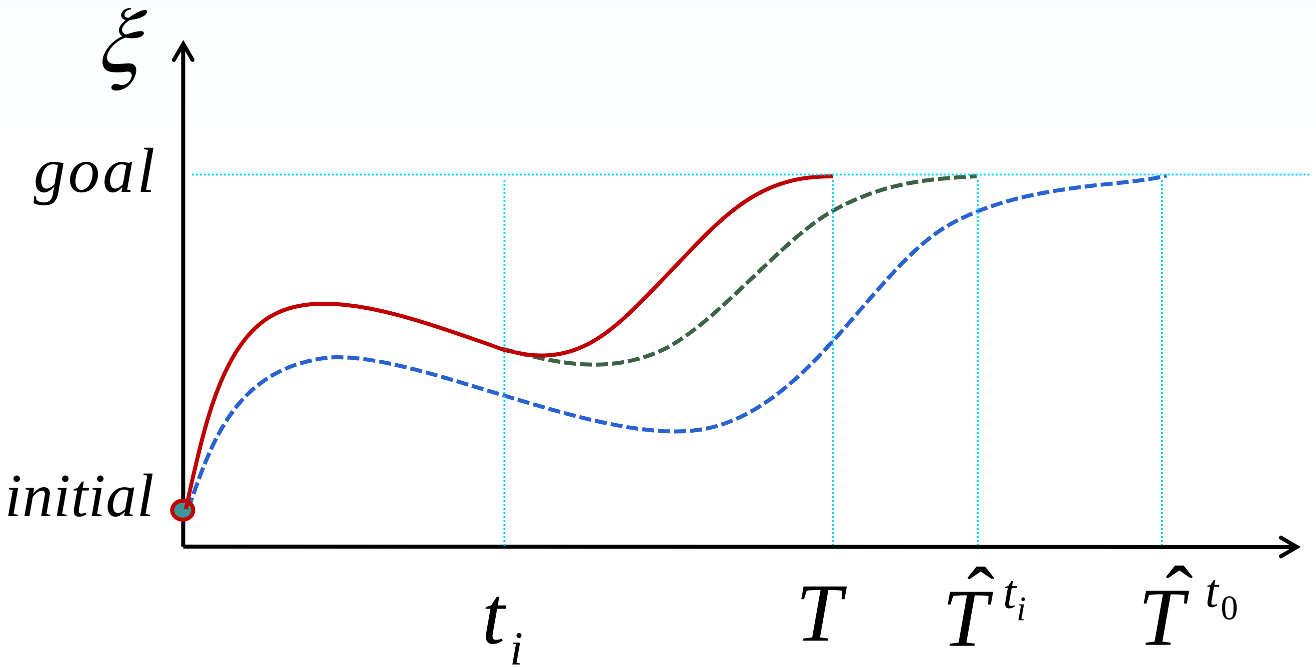
Position trajectory generation by velocity integration :

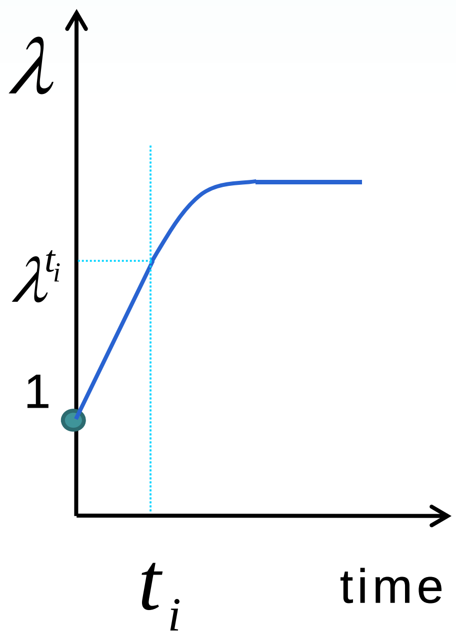
$$\xi^{t_{j+1}} = \xi^{t_j} + \lambda^{t_i} \sum_{l=1}^{L} \dot{\hat{\xi}}^{\left\{t_j + \frac{\Delta t}{L} l\right\}} \frac{\Delta t}{L}$$

Timing Controller :

$$\lambda^{t_{i+1}} = \lambda^{t_i} + k_p\left(\hat{T}^{t_i} - T\right) - k_d\left(\hat{T}^{t_i} - \hat{T}^{t_{i-1}}\right)$$

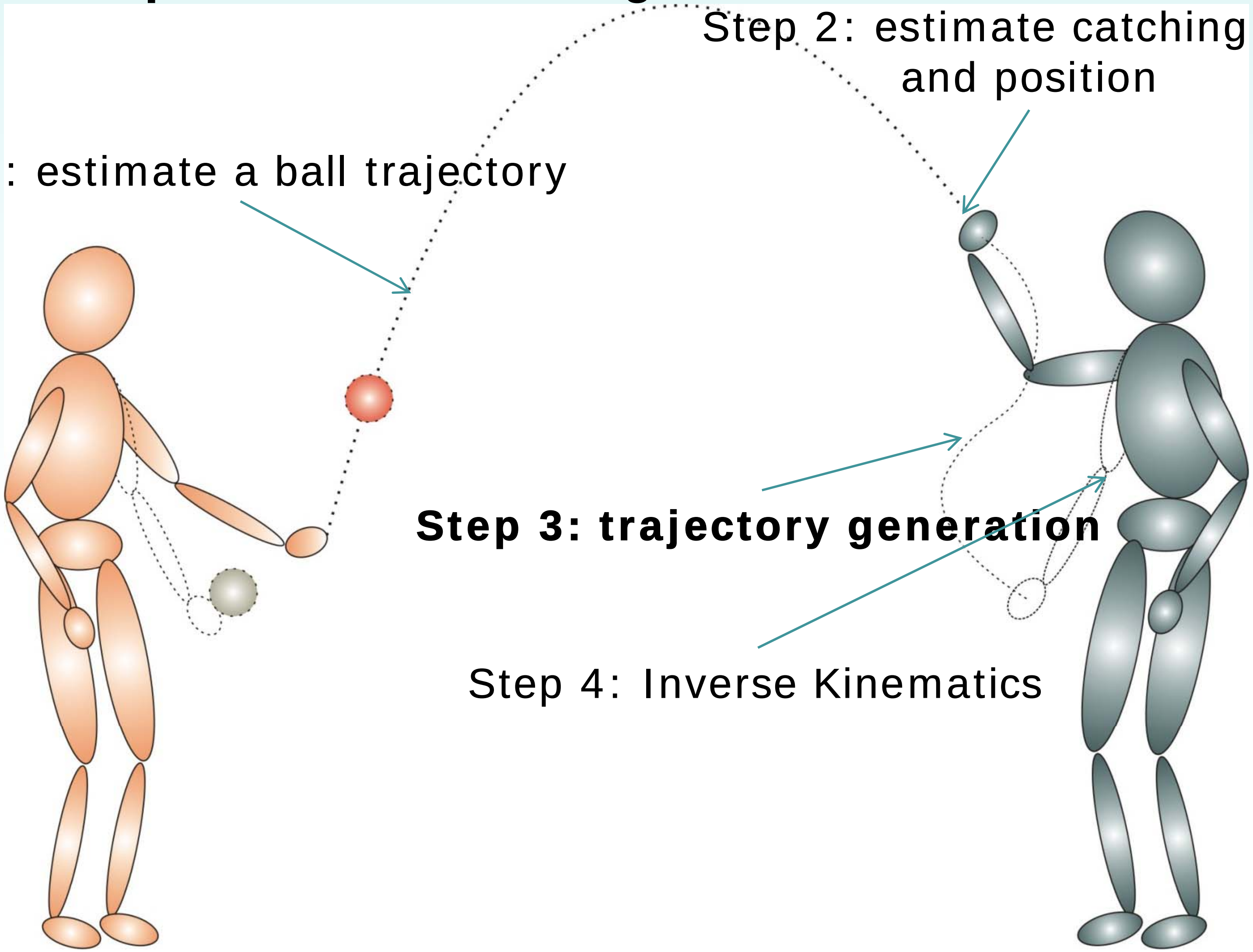
where t_i is a time at i^{th} controlling step,
$t_{i+1} = t_i + \Delta t,\ t_0 = 0;$
λ^{t_i} is a velocity multiplier, $\lambda^{t_0} = 1;$
k_p and k_d are the proportional and derivative gains respectively;
$\hat{T}^{t_i}$ is an estimated motion duration starting from the beginning of motion at time t_0 as calculated at time t_i





Catching a Ball on the fly(1/5)

4 Steps for Ball Catching



Catching a Ball on the fly (2/5)

Step 1 : Estimate the object's trajectory .

The ball's motion is modeled according to the ***Newtonian mechanics with the air drag****, and a trajectory of the ball is estimated using* ***Kalman filter*** [8]

Step 2 : Estimate the end-effector configuration at the catching moment and the duration of the robot's motion.

Choose the catching time and position ***to minimize the motion of the end-effector in the work-space*** *of a robot.* [9]

[8] A. L. Barker et al. 1995 *Computers and Mathematics with Applications*
[9] U. Frese et al. 2001 *Intelligent Robots and Systems*

Catching a Ball on the fly(3/5)

Step 3 : Generating **a task-space trajectory** of the motion that satisfies **temporal** and spatial constraints.

$$\xi = \{\mathbf{x}, \mathbf{o}, \rho\}$$

$\mathbf{x}$: Cartesian position $\in R^3$

$\mathbf{o}$: palm direction $\in R^3$ (2 DOF)

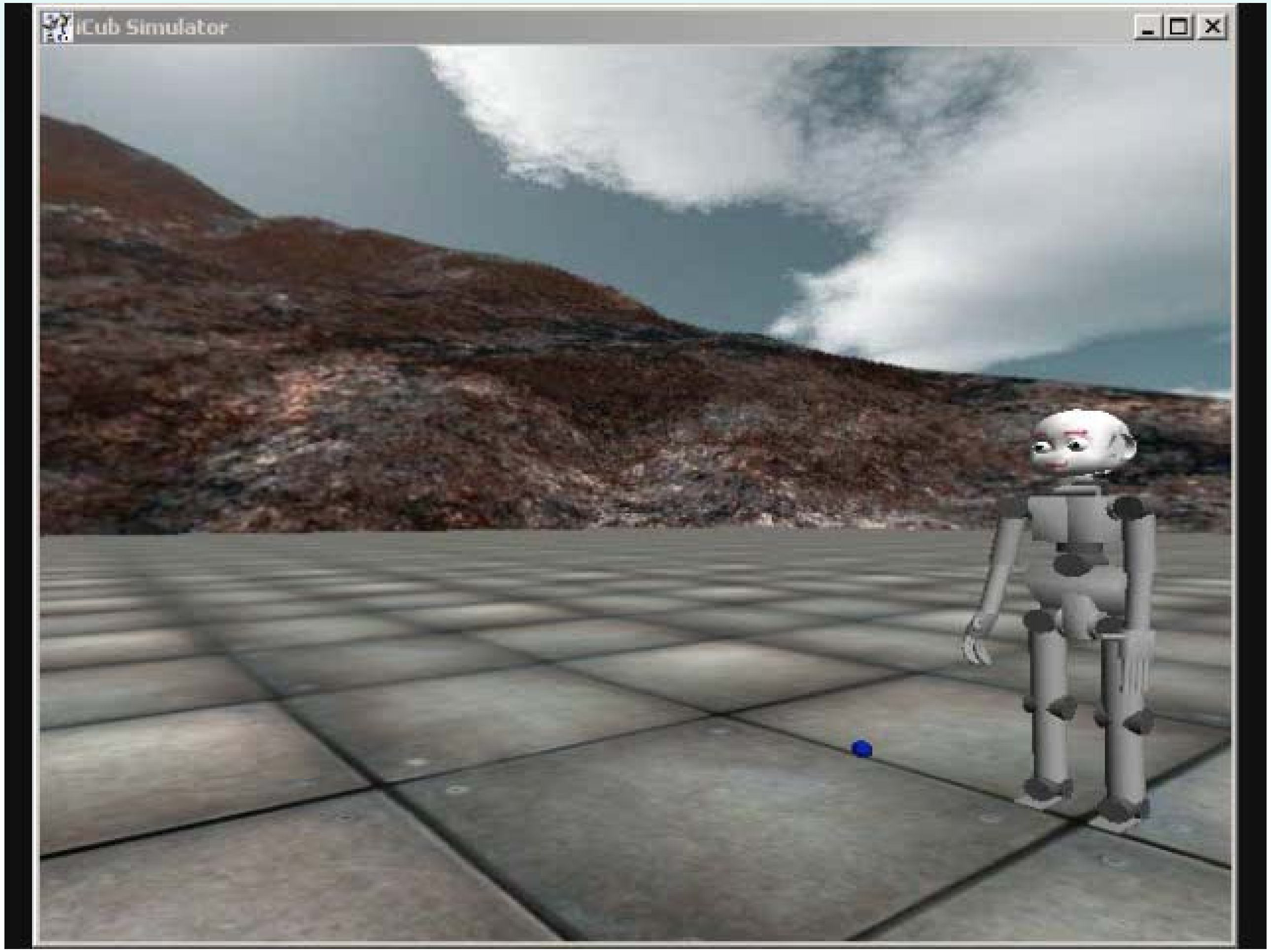
ρ : degree of grasping (fully stretched ~ grasping : 0.0 ~ 1.0)

Step 4 : Resolving the inverse kinematics to find a suitable joint angle configuration.

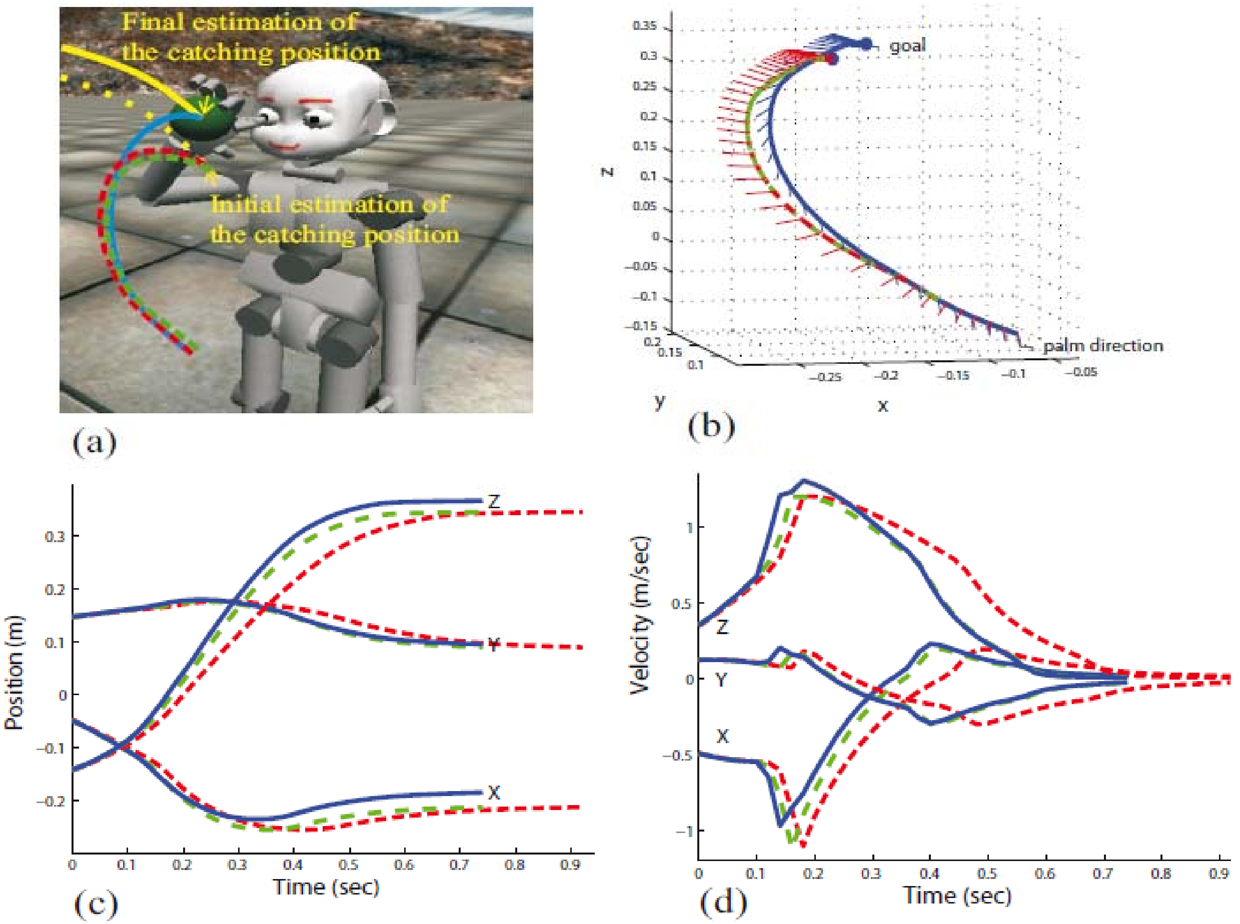
Damped least squares method using singular value decomposition (SVD) method [10]

[10] S. R. Buss et al. 2004

Catching a Ball on the fly(4/5)



Catching a Ball on the fly(5/5)



Trajectory generated for the initial estimation of the ball's catching position (without control over timing)

Trajectory generated for the initial estimation of the ball's catching position (with control over timing)

Trajectory generated for the final estimation of the ball's catching position (with control over timing)

Initial estimate of the ball's trajectory

Final estimate of the ball's trajectory

Conclusion and Future work

Conclusion

1. Encoding motions as autonomous **dynamical systems** (DS) provides an efficient way **to generate and adapt motions to external perturbations**, while ensuring **high accuracy** at the target .
2. Suggested method makes it possible to adhere to temporal constraint.
3. We validate the proposed method in an experiment where the iCub robot learns to catch a ball on the fly.

Future work

1. Estimation of non-linear movement of an object using DS.
2. Implementing the experiments on the actual physical robot.

Thank you