CS545—Contents XX

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    - Interprocessor communication (semaphore, shared semaphores, shared objects)
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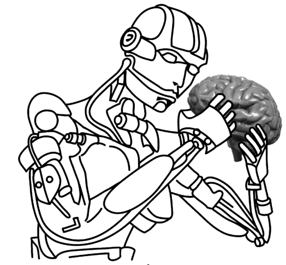
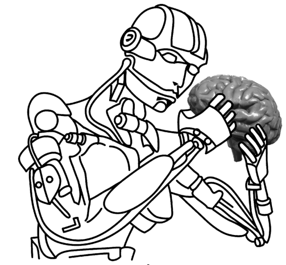
- Reading Assignment for Next Class
    - See http://www-clmc.usc.edu/~cs545

Goals of Gravity Compensation

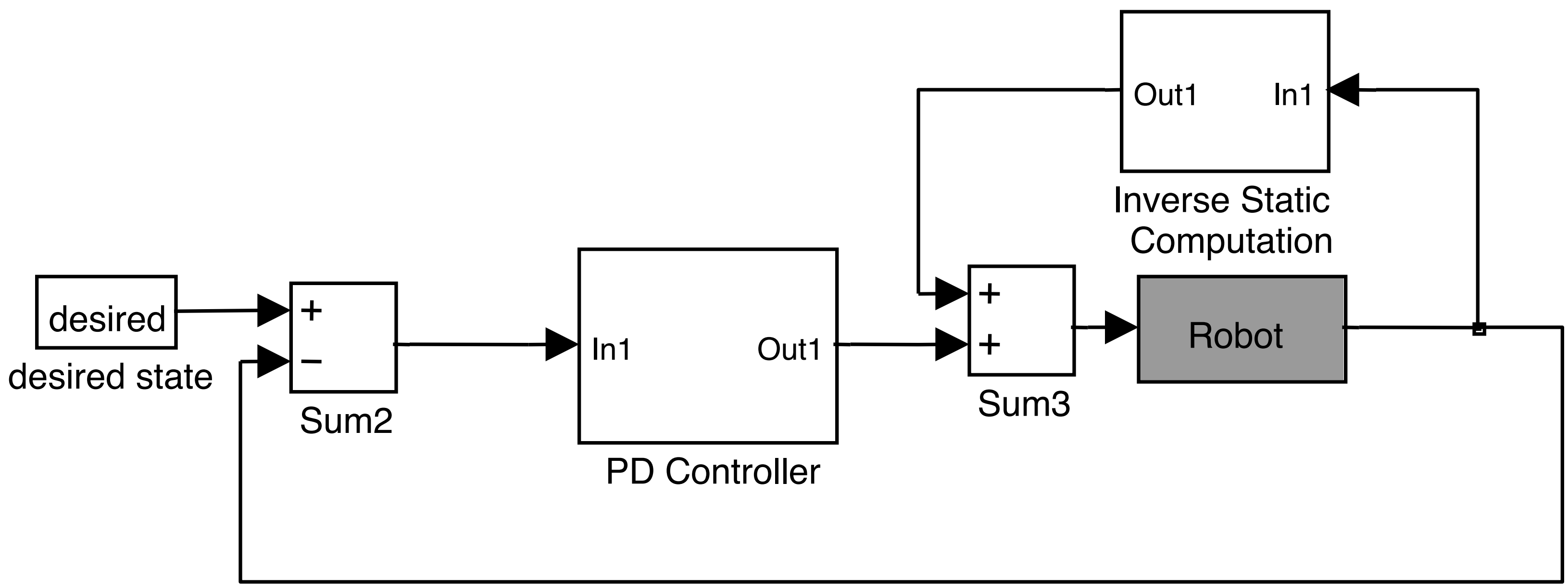


- Use the robot arm as a force reflecting manipulandum
  - Eliminate the weight due to gravity by supplying the appropriate feedforward commands at every moment of time
  - Afterwards, impose (program!) a virtual environment:
    - E.g., a “honey sphere” (in Cartesian Space!)
      - Inside of the sphere, impose viscous friction opposing the movement
      - Outside of the sphere, no viscous friction
- How dangerous is it to program this task?
- How would you do it?

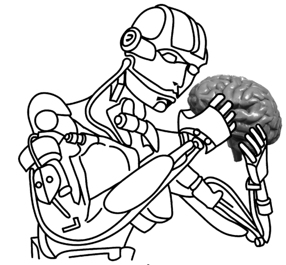
Theory Part I: Gravity Compensation

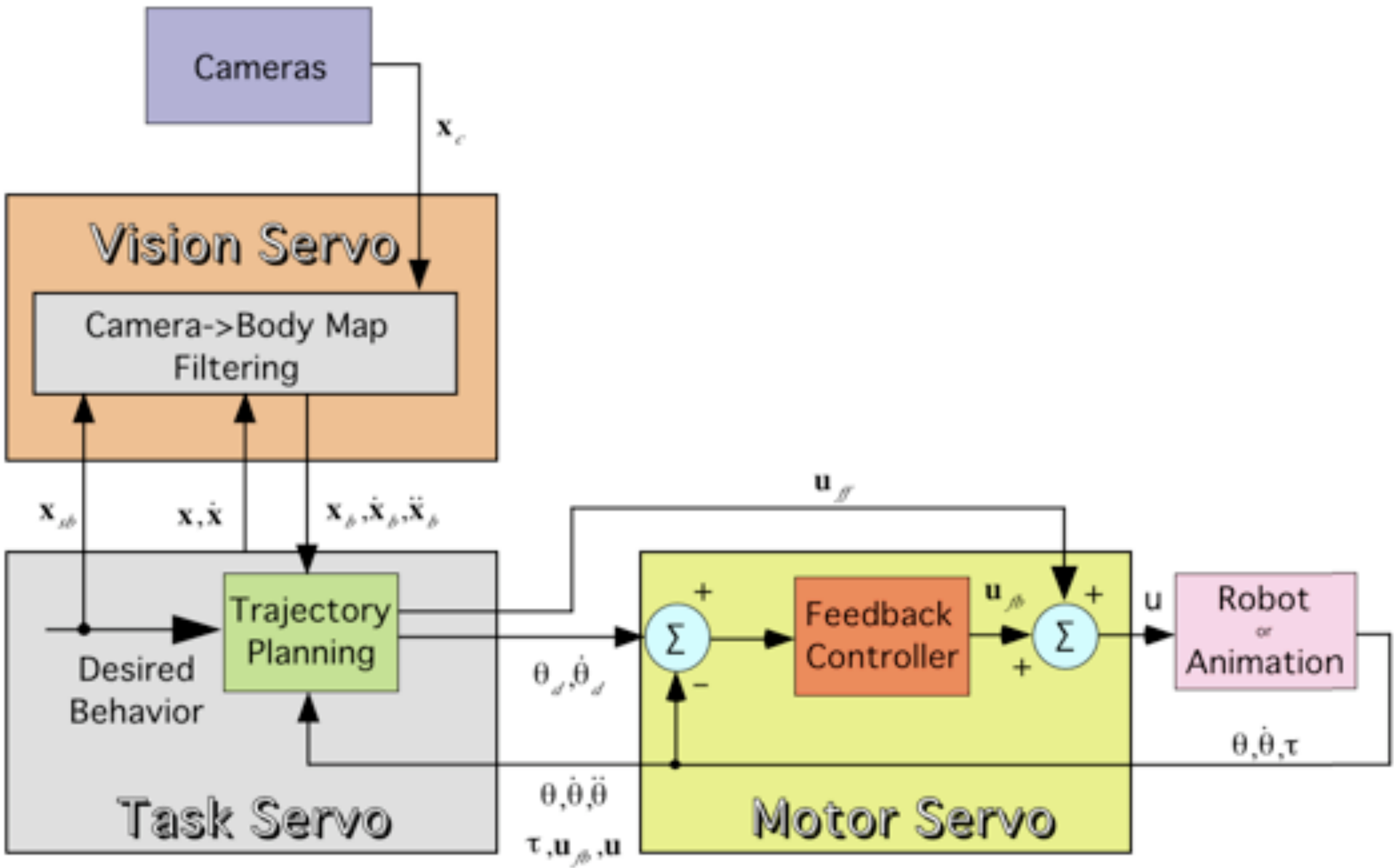


- At every time step:
  - Read current positions from sensors
  - Calculate inverse dynamics feedforward torque

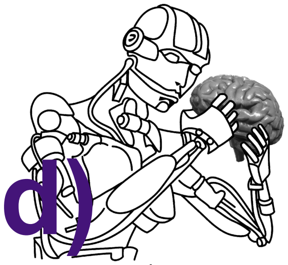


Control Loop on VxWorks





Gravity Compensation (cont'd)



- The Gravity Compensation Control Law

$$\mathbf{B}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}} + \mathbf{G}(\mathbf{q}) = \tau$$

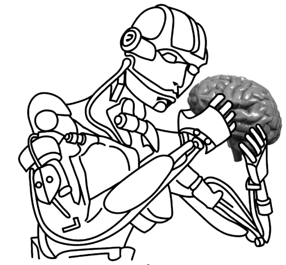
$$\mathbf{B}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}} + \mathbf{G}(\mathbf{q}) = \mathbf{G}(\mathbf{q}) + \mathbf{K}_P(\mathbf{q}_d - \mathbf{q}) + \mathbf{K}_D(\dot{\mathbf{q}}_d - \dot{\mathbf{q}})$$

$$\tau = \mathbf{G}(\mathbf{q}) + \mathbf{K}_P(\mathbf{q}_d - \mathbf{q}) + \mathbf{K}_D(\dot{\mathbf{q}}_d - \dot{\mathbf{q}})$$

•What is the desired position and velocity for the PD controller?

•What are the PD gains?

Gravity Compensation (cont'd)



- How to obtain **G**(**q**)?
  - Lagrange
  - Newton-Euler
- How to get the open parameters in **G**(**q**)?
  - Need mass and center of mass
  - Measure
  - Estimate
  - Estimate from data with regression methods

Automatic Generation of Inverse Dynamics

- Use Mathematica
  - Most important: Mathematica uses shift-return to execute commands
  - The relevant files: RigidBodyDynamics.m and arm2D.dyn will be made available on the web in HW IV.

Set the current working directory to the directory where the file RigidBodyDynamics.m is:

```
SetDirectory["Vangogh:Users:sschaal:current:courses:CS545:Lecture_XX"];
```

Load the Rigid Body Dynamics Package:

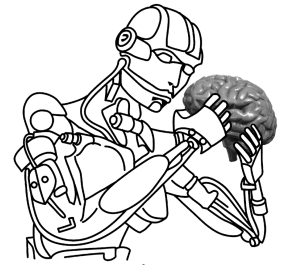
```
SetDirectory["ControlTheory"];
```

```
<<RigidBodyDynamics.m
```

Reset the path to the current directory

```
ResetDirectory[];
```

Automatic Generation of G(q) (cont;d)



```
ResetDirectory[];
```

Get some help information about this package:

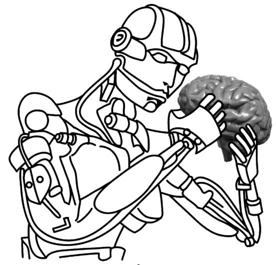
```
?InvDyn
```

```
InvDyn[infile, outfile,gravity] derives the inverse dynamics  equations from the specification
  in infile and dumps C-code output to outfile. The gravity vector in world coordinates is given (
  note that the gravity is supposed to be given WITH the appropriate sign!). The following rules apply:
 -input files are in Mathematica notation and can use Mathematica symbolic math
 -joints in the input file are numbered by integer numbers. DO NOT use the number 0 as it is used internally to
  refer to the base coordinate system. The numbers provided will be used as indices for arrays in the C-Code.
 -branches are permitted, but no loops.
 -each joint must rotate about one defined axis in its local coordinate system
 -each local coordinate system has is origin at the joint
 -the inertia tensor is in the center of mass coordinate system
 -rotation angles for coordinate transformation are alpha (rotate about x-axis),
  beta (rotate about y-axis), gamma (rotate about z-axis) in this  sequence, and in Euler angle notation
 -do NEVER use underscores and dashes in variable names in the input file (Mathematica syntax)
 -the rotation angles to get to the next local coordinate
  systems should be numerical (otherwise too much code, although this could be made more efficient)
```

Here comes a quick example how to use these functions. "arm2D.dyn" is a special input file that the user needs to generate manually. "arm2D" is the prefix that all generated C-code files will have. {0,0,G} is the direction of the gravity vector.

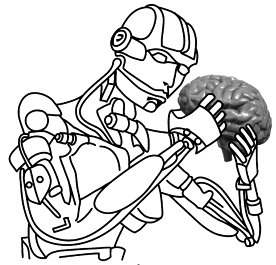
```
InvDyn["arm2D.dyn","arm2D",{0,0,G}];
```

The Structure of the Input File (*.dyn)



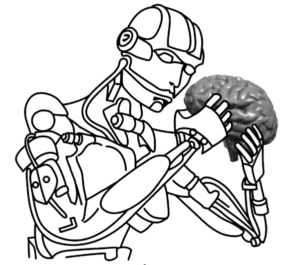
```
{
{jointID,{ID=1}},
{jointAxis,{0,0,1}},
{translation,{0,0,0}},
{rotationMatrix,{0,0,0}},
{successors,{2}},
{inertia,{{j111,j112,j113},{j112,j122,j123},{j113,j123,j133}}},
{centerMass, {xcm1,ycm1,zcm1}},
{mass,{m1}},
{jointVariables,{th1,th1d,th1dd,torque1,tex1}},
{extForce,{0,0,0,0,0,0}}
}
{
{jointID,{ID=2}},
{jointAxis,{0,0,1}},
{translation,{0,-l1,0}},
{rotationMatrix,{0,0,0}},
{successors,{}},
{inertia,{{j211,j212,j213},{j212,j222,j223},{j213,j223,j233}}},
{centerMass, {xcm2,ycm2,zcm2}},
{mass,{m2}},
{jointVariables,{th2,th2d,th2dd,torque2,tex2}},
{extForce,{0,0,0,0,0,0}}
}
```

For Gravity Compensation: thd*=thdd*=0!



```
{
{jointID,{ID=1}},
{jointAxis,{0,0,1}},
{translation,{0,0,0}},
{rotationMatrix,{0,0,0}},
{successors,{2}},
{inertia,{{j111,j112,j113},{j112,j122,j123},{j113,j123,j133}}},
{centerMass, {xcm1,ycm1,zcm1}},
{mass,{m1}},
{jointVariables,{th1,0,0,torque1,0}},
{extForce,{0,0,0,0,0,0}},
}
{
{jointID,{ID=2}},
{jointAxis,{0,0,1}},
{translation,{0,-l1,0}},
{rotationMatrix,{0,0,0}},
{successors,{}},
{inertia,{{j211,j212,j213},{j212,j222,j223},{j213,j223,j233}}},
{centerMass, {xcm2,ycm2,zcm2}},
{mass,{m2}},
{jointVariables,{th2,0,0,torque2,0}},
{extForce,{0,0,0,0,0,0}}
}
```

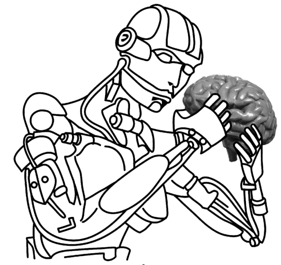
The Output Files of InvDyn:



- See file arm2D_InvDyn_math.h
- See file arm2D_InvDyn_declare.h
- See file arm2D_InvDyn_functions.h

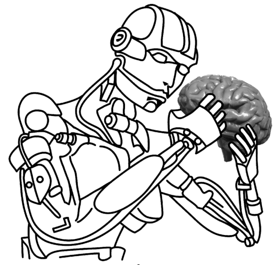
- See file arm2D_gcomp_InvDyn_math.h
- See file arm2D_gcomp_InvDyn_declare.h
- See file arm2D_gcomp_InvDyn_functions.h

What to do with these files?



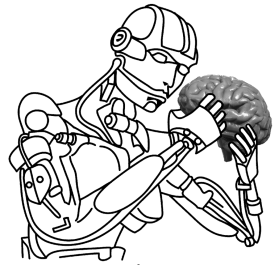
```
void
compute_gcomp(double *th, double *mass, double *xcm, double *ycm, double *zcm, double *torque)

{
#include "arm2D_gcomp_InvDyn_declare.h"
double th1,th2;
double xcm1,xcm2,ycm1,ycm2,zcm1,zcm2;
double m1,m2;
double l1=1.0;

th1=th[1];
th2=th[2];
xcm1=xcm[1];
xcm2=xcm[2];
ycm1=ycm[1];
ycm2=ycm[2];
zcm1=zcm[1];
zcm2=zcm[2];
m1 = mass[1];
m2 = mass[2];

#include "arm2D_gcomp_InvDyn_math.h"

torque[1] = torque1;
torque[2] = torque2;

}
```

Some Shortcuts to Make Things Easier



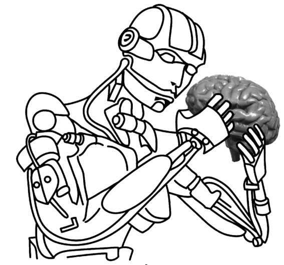
```
{
{jointID,{ID=1}},
{jointAxis,{0,0,1}},
{translation,{0,0,0}},
{rotationMatrix,{0,0,0}},
{successors,{2}},
{inertia,GenInertiaMatrixA["Inertia",ID]},
{centerMass, GenCMVectorA["cm",ID]},
{mass,GenMassA["m",ID]},
{jointVariables,{th[[1]],0,0,torque[[1]],0}},
{extForce,{0,0,0,0,0,0}}
}
{
{jointID,{ID=2}},
{jointAxis,{0,0,1}},
{translation,{0,-l1,0}},
{rotationMatrix,{0,0,0}},
{successors,{}},
{inertia,GenInertiaMatrixA["Inertia",ID]},
{centerMass, GenCMVectorA["cm",ID]},
{mass,GenMassA["m",ID]},
{jointVariables,{th[[2]],0,0,torque[[2]],0}},
{extForce,{0,0,0,0,0,0}}
}
```

The C-Program becomes



```
void
compute_gcomp(double *th, double *m, double **cm, double *torque)

{
#include "arm2D_gcomp_InvDyn_declare.h"


#include "arm2D_gcomp_InvDyn_math.h"

}
```

How To Program The "Honey Sphere"?



- In Joint Coordinates:
  - Within a certain joint angle range of each DOF, add a negative component to the feedforward command proportional to the current DOF velocity
- In Cartesian Coordinates:
  - Check whether the endeffector is in the sphere
  - If yes, calculate viscous friction force according to endeffector velocity
  - Convert viscous force into joint torques with Jacobian Transpose
  - A "cheap version": turn on viscous force in joint space if the endeffector is in the Cartesian sphere