# Teleoperaton in Surgery

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# Teleopera(on in Surgery

1. Introduc(on to Teleopera(on
2. History and State of the Art
3. Teleopera(on Control Concepts
4. Contact Force Es(ma(on
5. Iden(fica(on of Robot Dynamics
6. Example

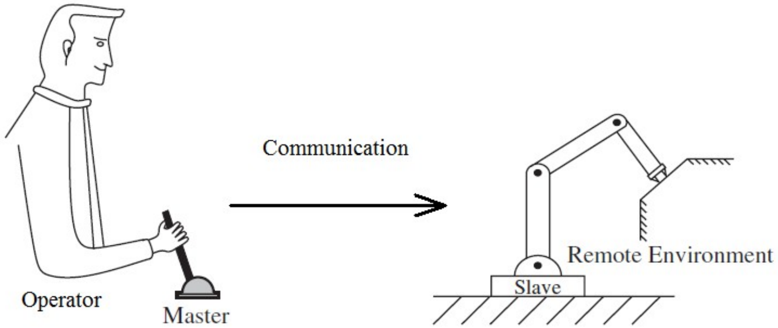
# Introduc(on to Teleopera(on

## What is teleopera(on?

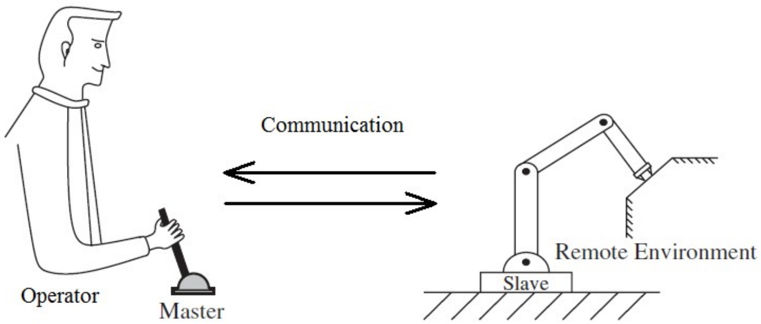
Defini(on of teleopera(on (www.wikipedia.org):

*"… opera)on of a machine at a distance …"*

- Unilateral teleopera(on:



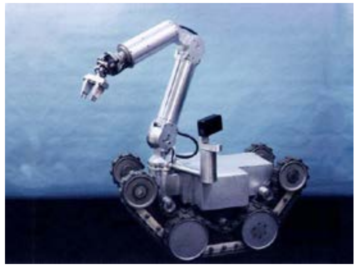

- Bilateral teleopera(on:

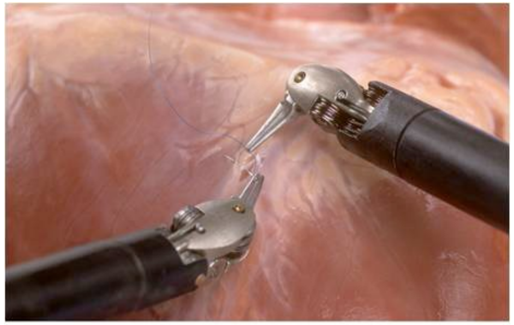


# Introduc(on to Teleopera(on

## Applica(on Examples

- Hazardous materials and areas
- Mobile robots
- Space
- Surgery
- Video games

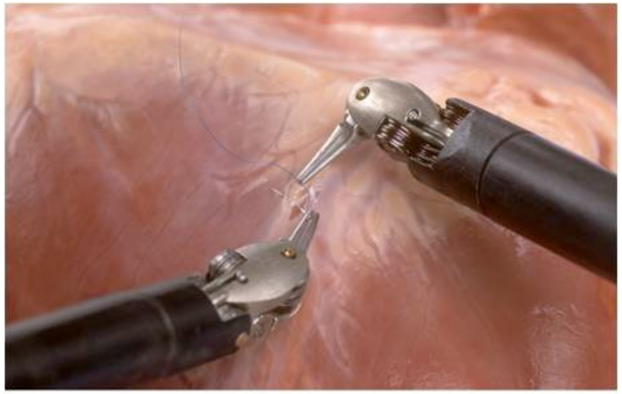


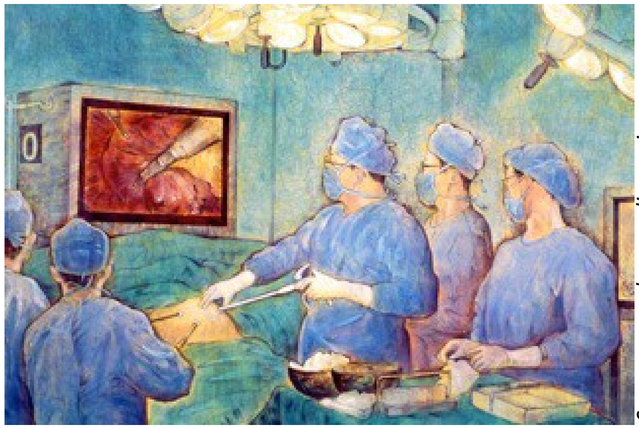
# Introduc(on to Teleopera(on

## Robo(c Surgery

- Enables remote surgery
- Typically used in minimally invasive surgery
- Gives the surgeon small wrists inside the body
- Surgeon mo(on can be scaled for microsurgery
- Can remove surgeon tremor



*Source: www.intui)vesurgical.com*



*Source: www.kenzmedico.co.jp*

# History and State of the Art

## The ZEUS® Surgical System

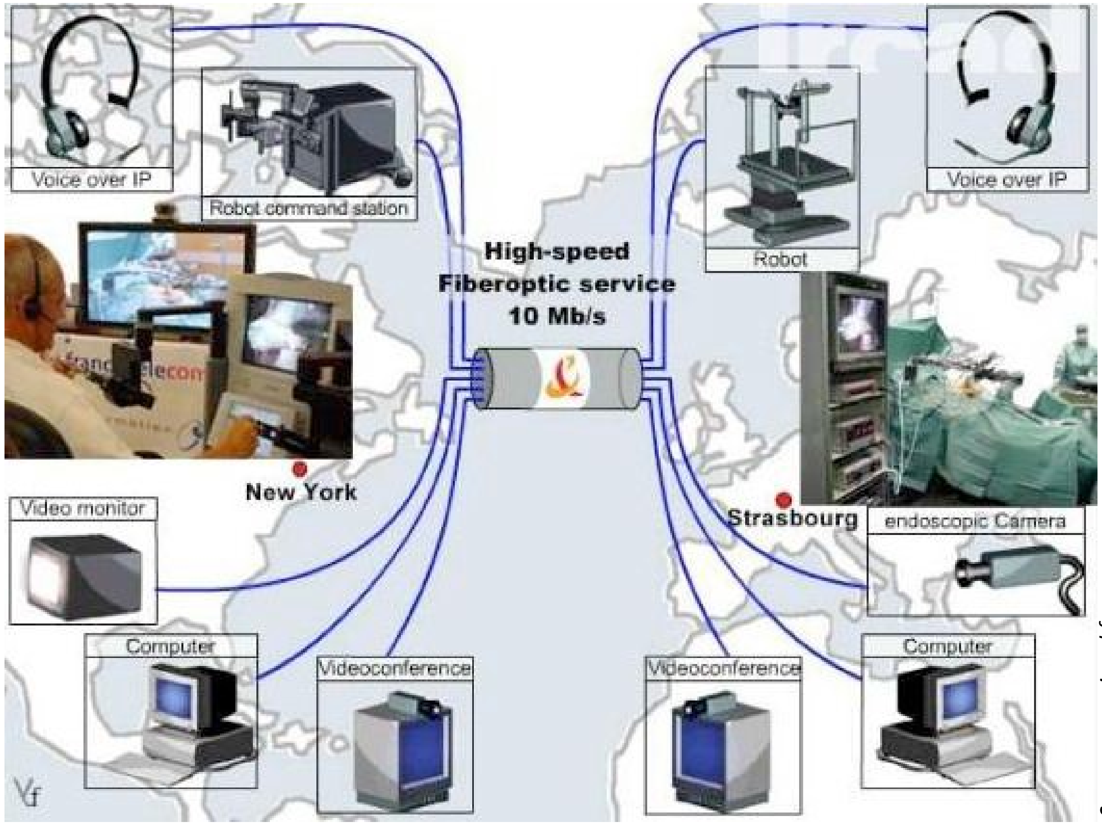
- ComputerMo(on Inc., USA (now part of Intui(ve Surgical Inc.)
- World's first robot for surgery
- Received CE marking in 1998 and FDA clearance in 2001
- Developed for laparoscopic and thoracoscopic surgery
- Consists of three table-mounted robo(c arms (slave), controlled by the surgeon from a separate console (master)
- Unilateral teleopera(on

*Source: www.pmdcorp.com*

# History and State of the Art

## Opera(on Lindbergh, 7 September 2001

- Prof. Jacques Marescaux, IRCAD France
- First successful transatlan(c robo(c surgery, from New York to Strasbourg
- 45-minute procedure, gallbladder removal
- Roundtrip communica(on delay of 150ms




*Source: www.ircad.fr*

# History and State of the Art

## The daVinci® Surgical System

- Intui(ve Surgical Inc., USA
- Today's only commercially available robot for tele-surgery
- Received CE marking in 1999 and FDA clearance in 2000
- Consists of a pa(ent-side cart (slave) with three arms and a surgeon console (master)
- EndoWrist® technology mimics the human hand inside the pa(ent
- Unilateral teleopera(on

Source: www.intui(vesurgical.com

# History and State of the Art

## Today and into the Future

- Only one robot for tele-surgery on the market (daVinci)
- Around 1000 daVinci systems installed worldwide
- 3 daVinci systems in Norway (2 at Oslo University Hospital and 1 at Telemark Hospital Skien)
- Common procedures include cardiac bypass surgery, prostatectomy and hysterectomy
- Two major technical challenges to be solved:
  - Time delay
  - Force feedback

# Teleopera(on Control Concepts

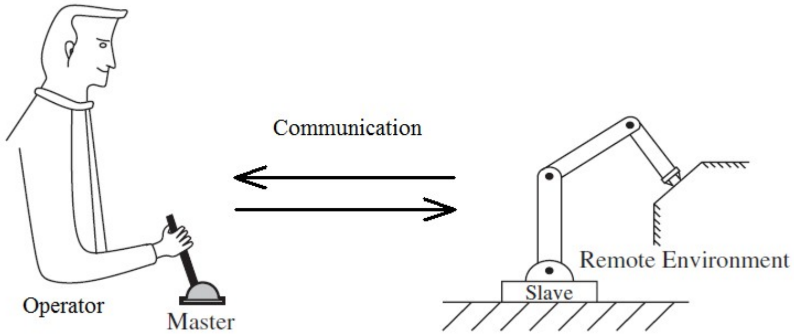
## Modeling a 1-DoF Linear Teleoperator

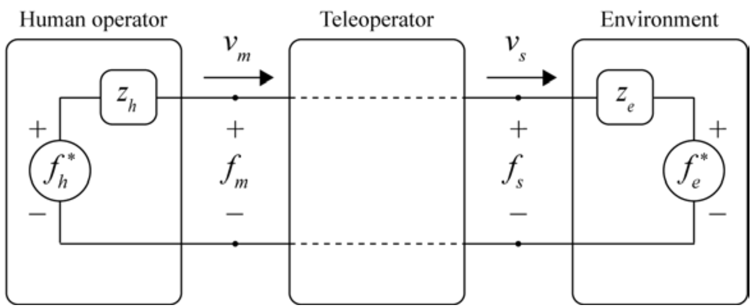
- The two-port network model
  - Energy ($P = fv$) exchange takes place at two loca(ons, or ports
- The hybrid matrix representa(on

$$\begin{bmatrix} f_m \\ -v_s \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} v_m \\ f_s \end{bmatrix} = H \begin{bmatrix} v_m \\ f_s \end{bmatrix}$$

- The ideal (transparent) teleoperator

$$\begin{matrix} f_m = f_s \\ v_m = v_s \end{matrix} \quad \Rightarrow \quad H = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}$$



# Teleopera(on Control Concepts

## The Extended Lawrence Architecture (ELA)

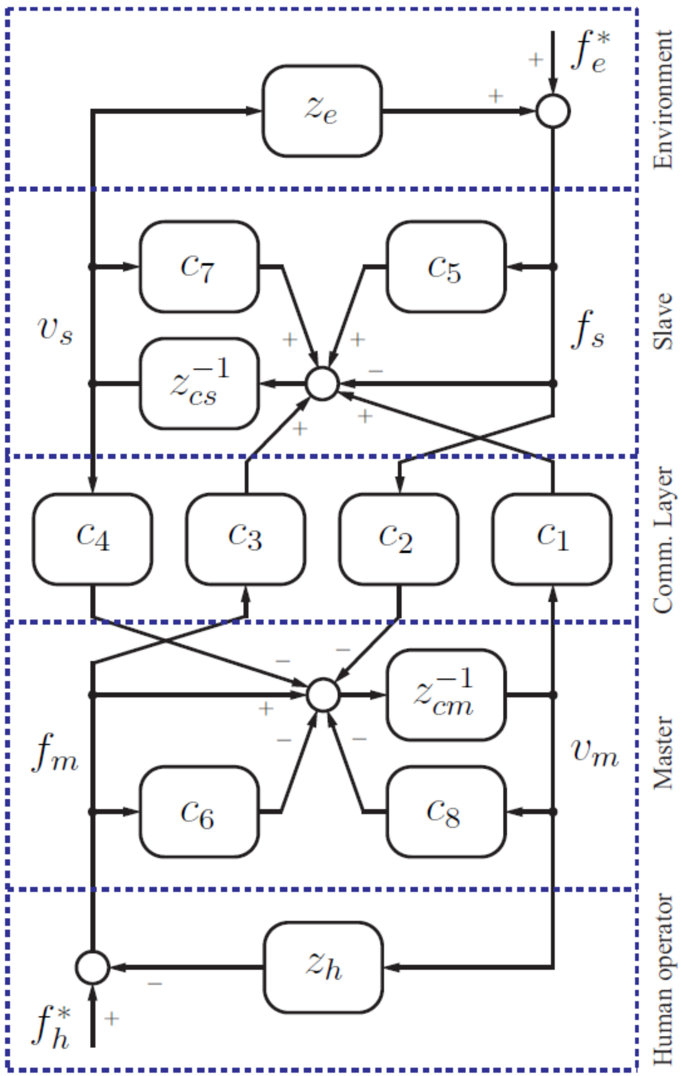
- Introduced by Lawrence in 1993
- All dynamics are on the form

$$z = ms + b + k/s$$

- Transparency (from hybrid matrix):

$$c_1 = z_{cs} - c_7$$
$$c_2 = 1 - c_6$$
$$c_3 = 1 - c_5$$
$$c_4 = -(z_{cm} + c_8)$$

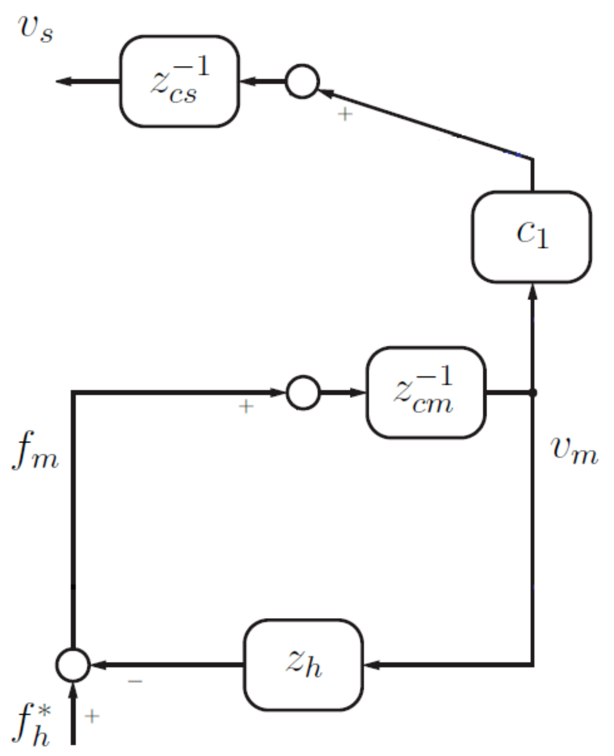
- Famous tradeoff: transparency vs. stability



# Teleopera(on Control Concepts

## Example: Unilateral Teleopera(on

- We want the slave to track the master
- No touching of the environment ($z_e = 0$)
- No local force controllers ($c_5 = c_6 = 0$)
- No local posi(on controllers ($c_7 = c_8 = 0$)
- Only master velocity is sent across the communica(on layer ($c_2 = c_3 = c_4 = 0$)
- The only gain to choose is $c_1$, which can be set to obtain desired tracking performance



# Contact Force Es(ma(on

## Rela(on to Teleopera(on in Surgery

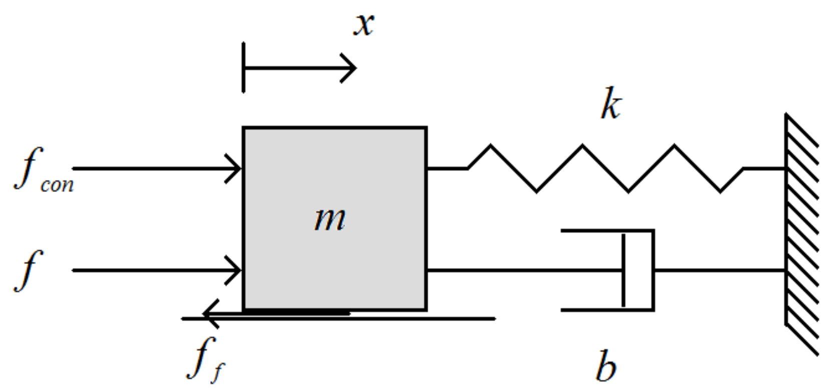
- Research suggests that it would be favorable to have force feedback in robo(c tele-surgical systems
- Realis(c force feedback in bilateral teleopera(on requires the knowledge of contact forces
- The use of force sensors in robo(c minimally invasive surgery introduces challenges related to
    - Size and cost
    - Sterilizability and disposability
    - Wiring and electronics
    - Noise and bandwidth

Source: www.intui)vesurgical.com

Source: www.a)-ia.com

# Contact Force Es(ma(on

## Basic Principle




- Given a mass-damper-spring system:

$$m\ddot{x} + b\dot{x} + kx + f_f = f + f_{con}$$

- Solve for the contact force:

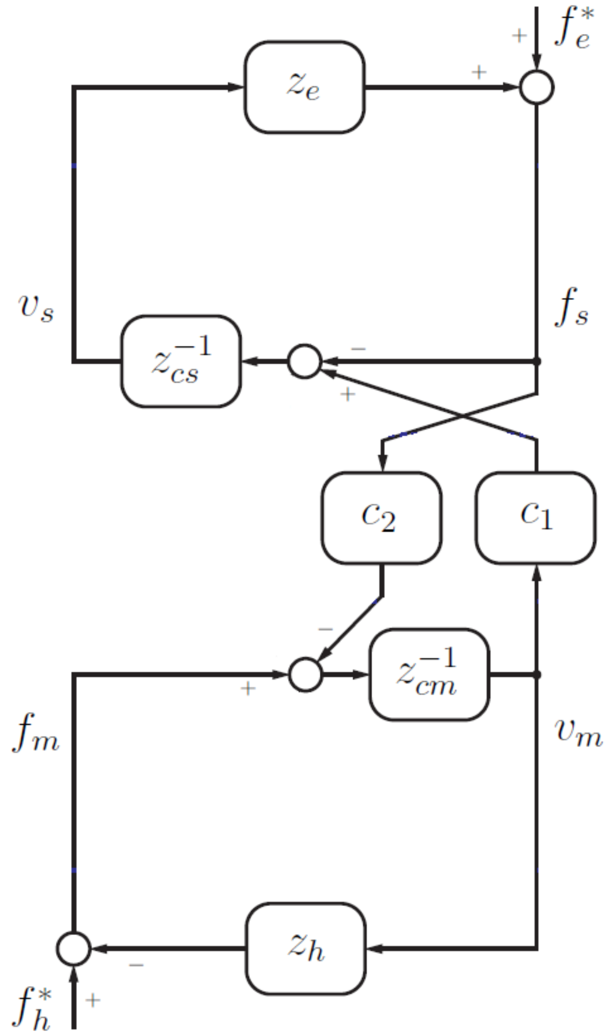
$$f_{con} = f - m\ddot{x} - b\dot{x} - kx - f_f$$

- Challenges:
    - Velocity and accelera(on measurement
    - Iden(fica(on of fric(on forces

# Contact Force Es(ma(on

## Teleopera(on example: Forward-Flow Controller

- Common bilateral teleopera(on controller
- No local force controllers ($c_5 = c_6 = 0$)
- No local posi(on controllers ($c_7 = c_8 = 0$)
- Velocity is sent from master to slave, and force is sent from slave to master ($c_3 = c_4 = 0$)
- The gain $c_1$ is chosen for posi(on tracking, and the gain $c_2$ is chosen for force tracking
- A force sensor is needed to measure the slave contact force $f_s$



# Contact Force Es(ma(on

## Teleopera(on example: Forward-Flow Controller

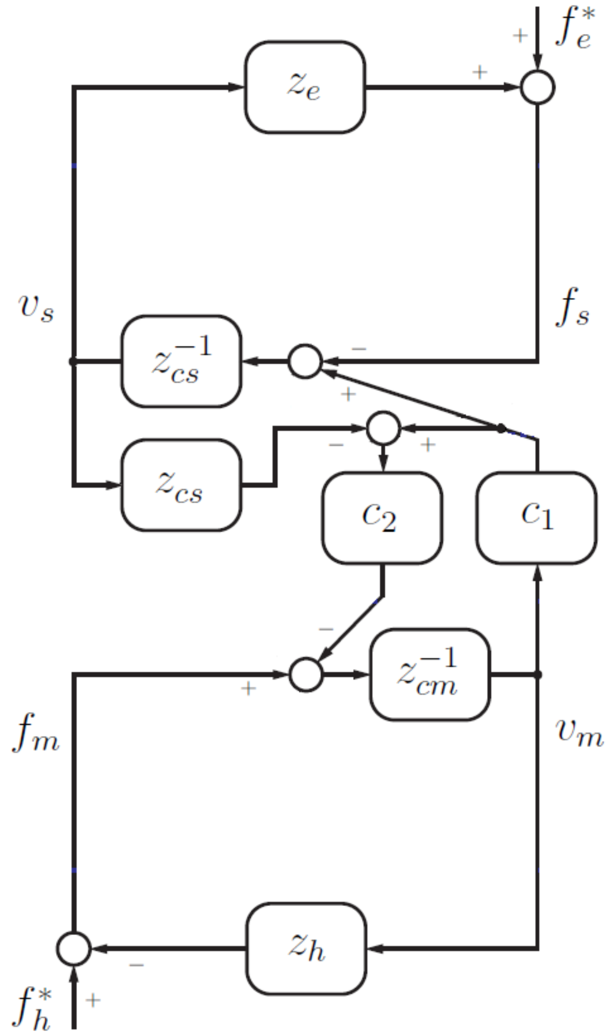
- Assume there is no force sensor on slave side
- Slave dynamics are given as

$$v_s = z_{cs}^{-1}(c_1 v_m - f_s)$$

- Thus slave contact force can be es(mated as

$$f_s = c_1 v_m - z_{cs} v_s$$

- The force-sensor-free controller is equivalent to the regular forward-flow controller



# Iden(fica(on of Robot Dynamics

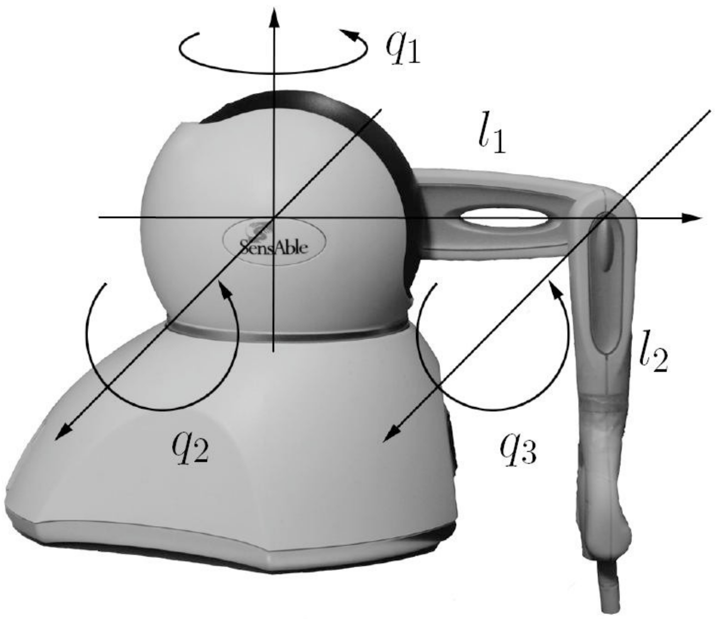
## Separa(on of the Unknown Parameters

- Mass-damper-spring system (ignore fric(on):

$$m\ddot{x} + b\dot{x} + kx = f$$
$$\Downarrow$$
$$[\ddot{x} \quad \dot{x} \quad x][m \quad b \quad k]^T = f$$
$$\Downarrow$$
$$Y(\ddot{x}, \dot{x}, x)\varphi = f$$

- General $n$-DoF robot:

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + N(q) = \tau$$
$$\Downarrow$$
$$Y(\ddot{q}, \dot{q}, q)\varphi = \tau$$



# Iden(fica(on of Robot Dynamics

## Recursive Least Squares for Parameter Iden(fica(on

- Collect data while exci(ng all the modes of the robot's dynamics
- Update the parameter es(mate $\hat{\varphi}$ recursively according to the following algorithm:

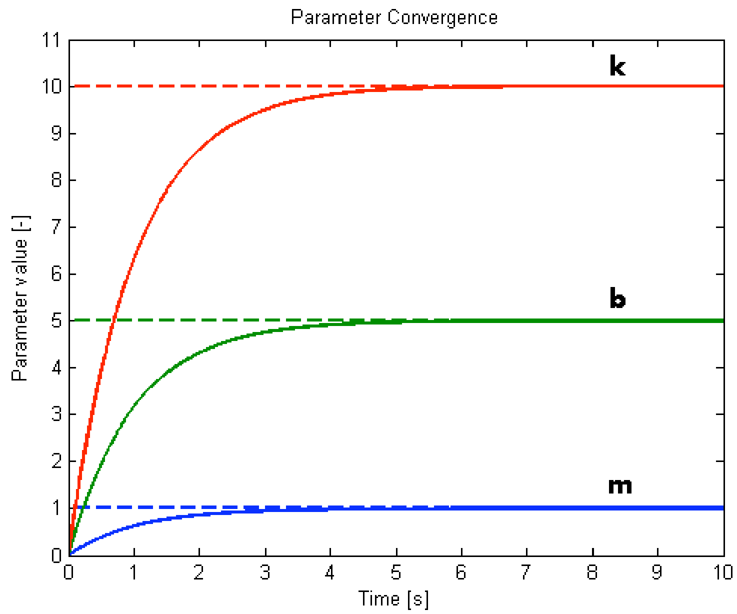
$$e = \tau - \hat{\tau} = \tau - Y\hat{\varphi}$$

$$\dot{P} = \beta P - PY^T YP$$

$$\dot{\hat{\varphi}} = PY^T e$$

- The algorithm can also be run off-line
- Fric(on is considered to be noise at this stage

$$\ddot{x} + 5\dot{x} + 10x = f$$



# Iden(fica(on of Robot Dynamics

## Fric(on Iden(fica(on with Wavelets

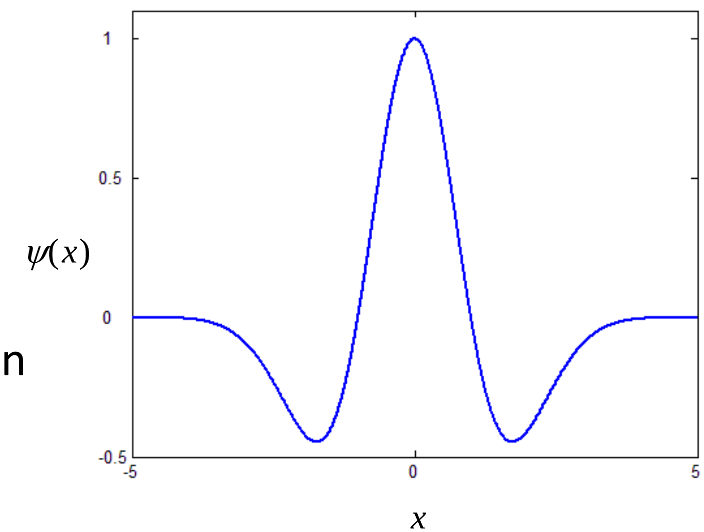
- Wavelets can be used to reconstruct func(ons
- A fric(on model can be regarded as such a func(on
- A wavelet is itself a func(on, for example

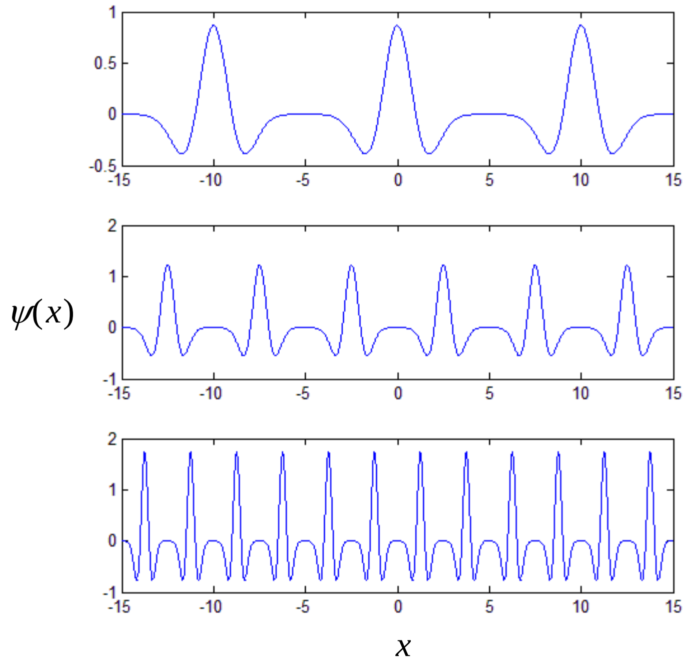
$$\psi(x) = (1 - x^2)e^{-x^2/2}$$

- Wavelet theory states that a func(on $f(x) \in L^2$ can be exactly reconstructed with an infinite weighted wavelet expansion (network) as

$$f(x) = \sum_{i=-\infty}^{\infty} c_i \psi_i(x)$$

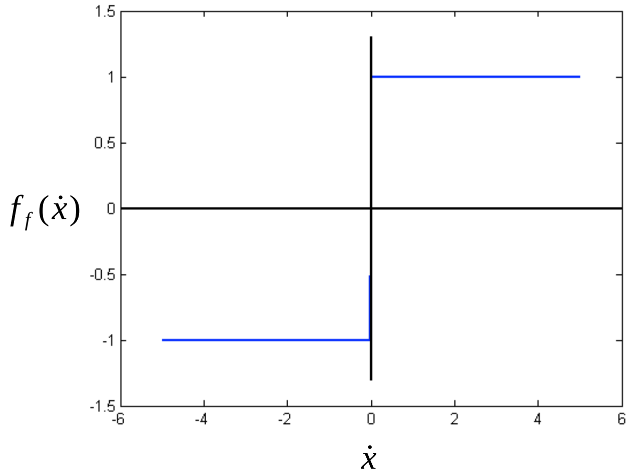
- In prac(ce we use a network of *finite* size



# Iden(fica(on of Robot Dynamics

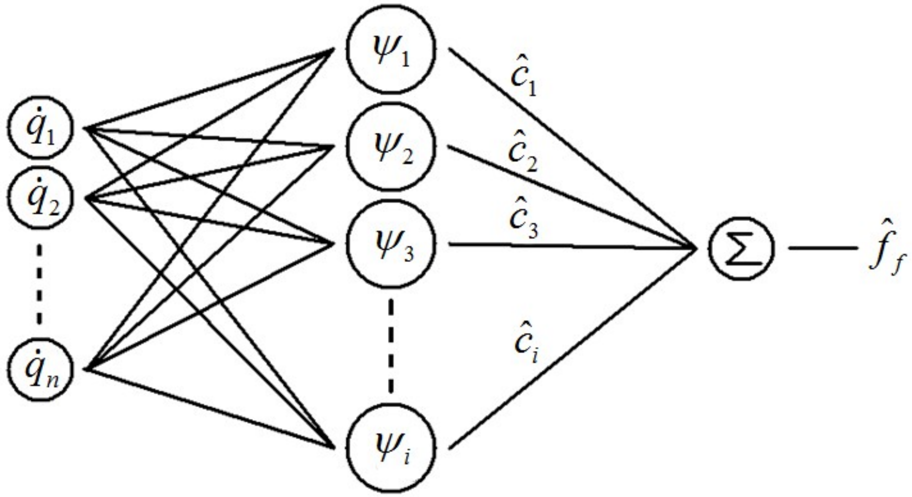
## Fric(on Iden(fica(on with Wavelets




- Coulomb fric(on is a common fric(on model
- With wavelets no specific model is adopted, rather the fric(on is learned by the wavelet network
- In the case of the mass-damper-spring system:

$$\hat{f}_f(\dot{x}) = \sum_i \hat{c}_i \psi_i(\dot{x})$$

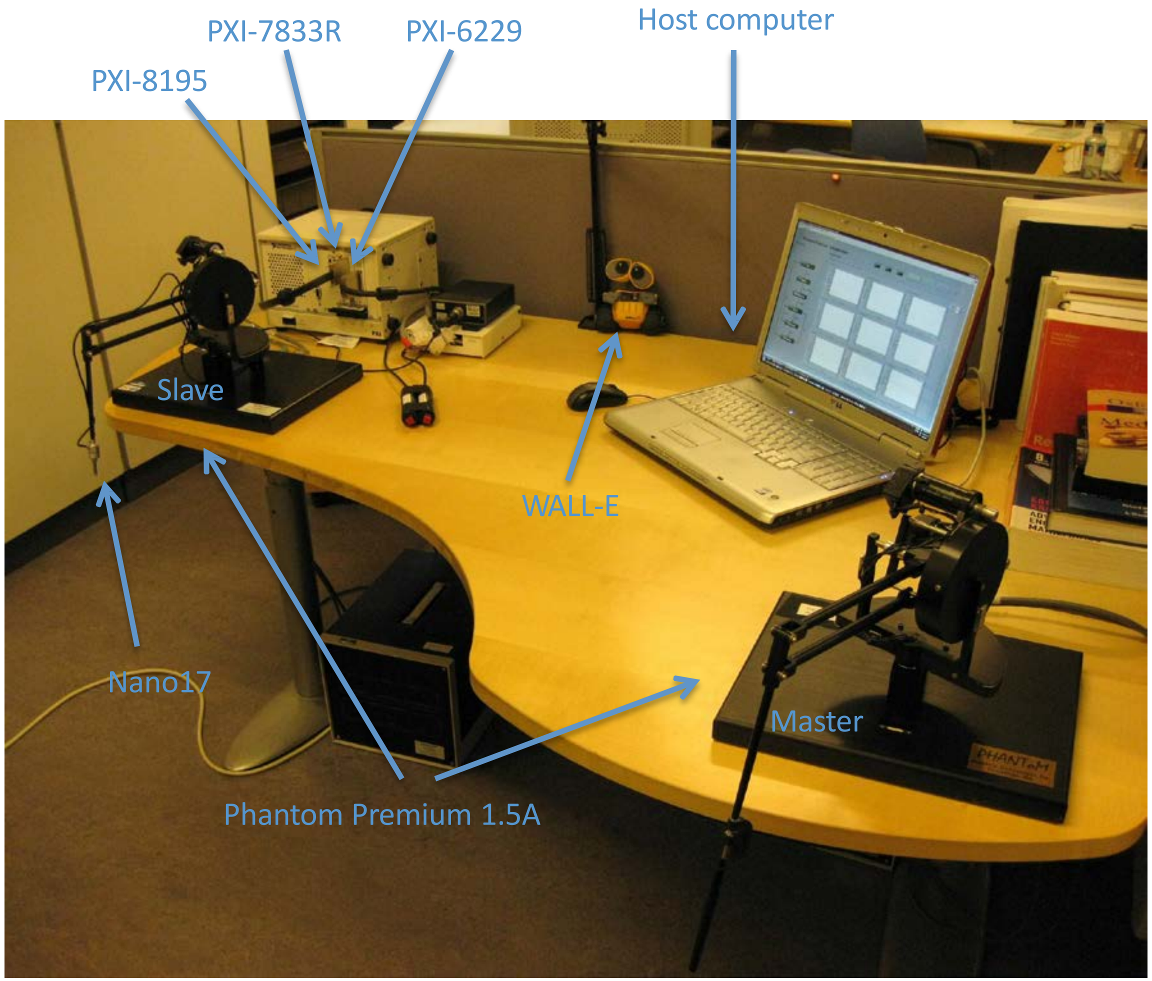
- A wavelet network can also be used in mul(-dimensional cases, and can be regarded as a neural network



# An Experimental Setup for Teleopera(on

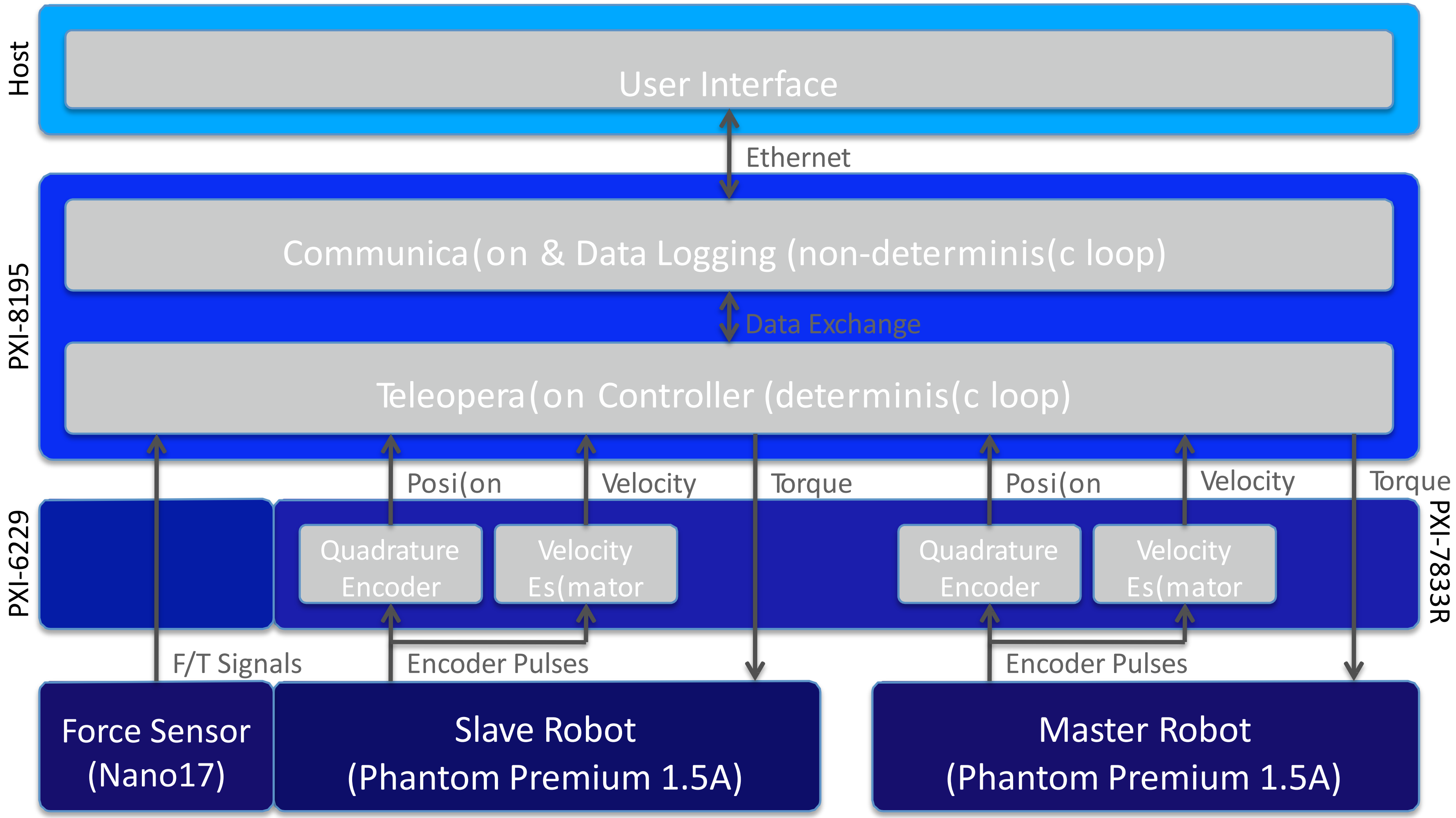
## Hardware Components

- Two Phantom Premium 1.5A hap(c devices from SensAble Technologies
- One 6-DoF force/torque sensor (Nano17) from ATI
- One NI PXI embedded controller (PXI-8195)
- One NI RIO DAQ card (PXI-7833R)
- One NI M-series DAQ card (PXI-6229)
- One host computer



# An Experimental Setup for Teleopera(on

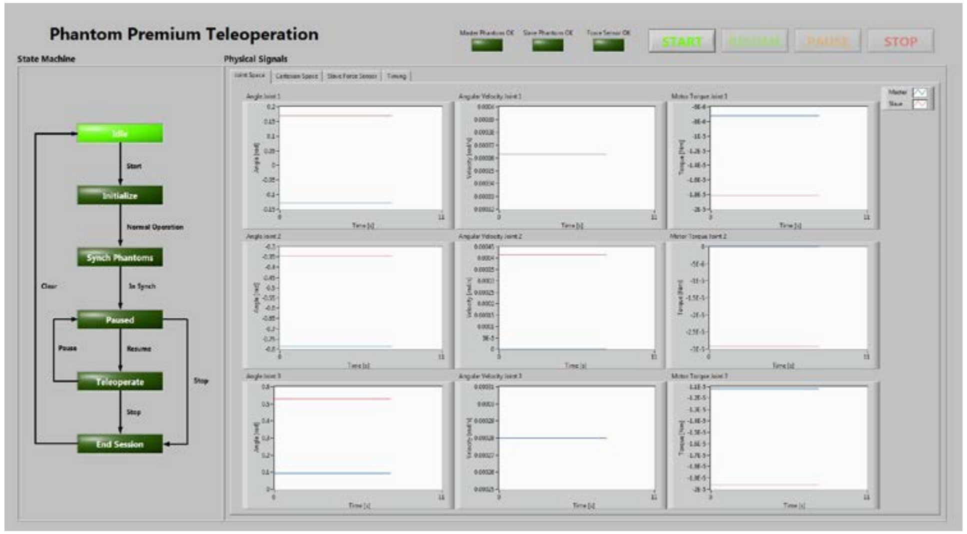
## System Architecture

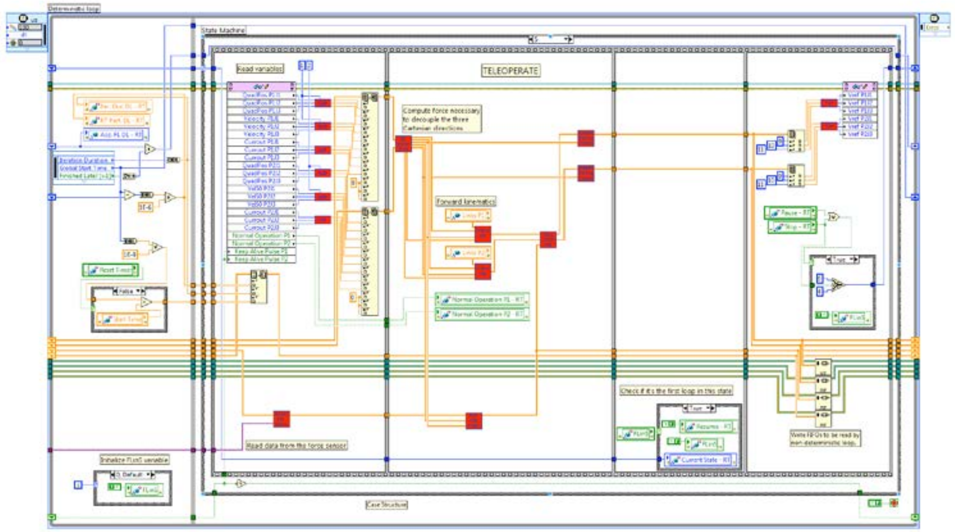


# An Experimental Setup for Teleopera(on

## LabVIEW Sopware

- LabVIEW is a high-level graphical programming language
- User interfaces easy to implement
- Performance (speed) comparable to C
- The sopware package includes
  - LabVIEW 8.6 Core
  - LabVIEW Real-Time Module 8.6
  - LabVIEW FPGA Module 8.6



# An Experimental Setup for Teleopera(on

## Phantom Premium Dynamics

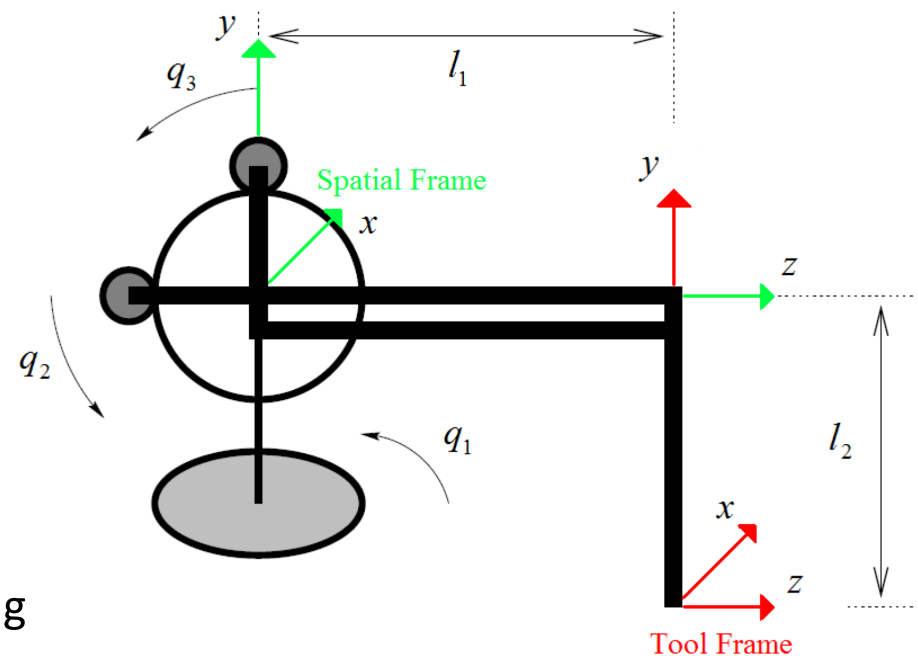
- What we want:

$$m_x \ddot{x} = f_x, \qquad m_y \ddot{y} = f_y, \qquad m_z \ddot{z} = f_z$$

- What we have:

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + N(q) = \tau$$

$$q = [q_1, q_2, q_3]^T \in R^3$$




- Decouple the dynamics using
  - The forward kinema(cs
  - The Jacobian of the forward mapping
  - Iden(fica(on of the unknown parameters

# An Experimental Setup for Teleopera(on

## Phantom Premium Forward Kinema(cs

- A homogeneous transforma(on matrix $g_{st}(q)$ describing the configura(on of the tool frame rela(ve to the spa(al frame

$$g = \begin{bmatrix} R & p \\ 0 & 1 \end{bmatrix}, \qquad p = \begin{bmatrix} x \\ y \\ z \end{bmatrix}$$

- Ini(al configura(on:

$$g_{st}(0) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & -l_2 \\ 0 & 0 & 1 & l_1 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

- Configura(on as a func(on of $q$:

$R$ $p$

$$g_{st}(q) = \begin{bmatrix} \cos(q_1) & -\sin(q_1)\sin(q_3) & \sin(q_1)\cos(q_3) & l_1\sin(q_1)\cos(q_2) + l_2\sin(q_1)\sin(q_3) \\ 0 & \cos(q_3) & \sin(q_3) & l_1\sin(q_2) - l_2\cos(q_3) \\ -\sin(q_1) & -\cos(q_1)\sin(q_3) & \cos(q_1)\cos(q_3) & l_1\cos(q_1)\cos(q_2) + l_2\cos(q_1)\sin(q_3) \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

# An Experimental Setup for Teleopera(on

## Jacobian of the Forward Mapping

- The forward mapping $p$:

$$p = f(q) = \begin{bmatrix} l_1 \sin(q_1)\cos(q_2) + l_2 \sin(q_1)\sin(q_3) \\ l_1 \sin(q_2) - l_2 \cos(q_3) \\ l_1 \cos(q_1)\cos(q_2) + l_2 \cos(q_1)\sin(q_3) \end{bmatrix}$$

- The Jacobian $J$ of the forward mapping relates joint velocity $\dot{q}$ to Cartesian velocity $\dot{p}$

$$\dot{p} = \frac{\partial f}{\partial q}\dot{q} = J\dot{q}$$

$$J = \frac{\partial f}{\partial q} = \begin{bmatrix} l_1 \cos(q_1)\cos(q_2) + l_2 \cos(q_1)\sin(q_3) & -l_1 \sin(q_1)\sin(q_2) & l_2 \sin(q_1)\cos(q_3) \\ 0 & l_1 \cos(q_2) & l_2 \sin(q_3) \\ -l_1 \sin(q_1)\cos(q_2) - l_2 \sin(q_1)\sin(q_3) & -l_1 \cos(q_1)\sin(q_2) & l_2 \cos(q_1)\cos(q_3) \end{bmatrix}$$

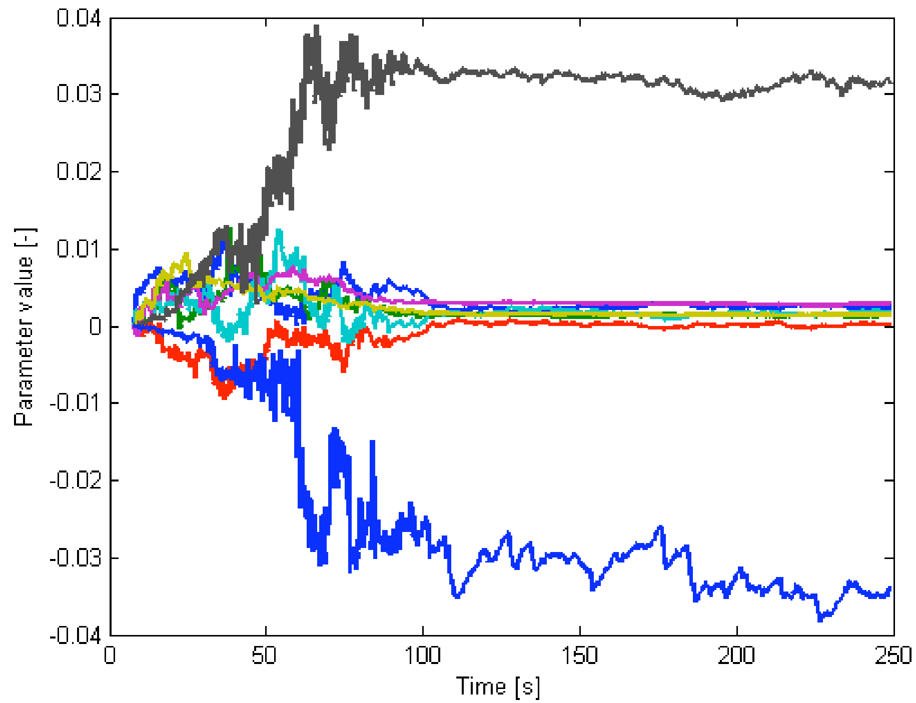
# An Experimental Setup for Teleopera(on

## Iden(fica(on of the Unknown Parameters

- Remember

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + N(q) = \tau$$
$$\Downarrow$$
$$Y(\ddot{q},\dot{q},q)\varphi = \tau$$

- For the Phantom Premium 1.5A, $Y \in R^{3x8}$ and $\varphi \in R^{8}$
- Once the parameter vector $\varphi$ has been found the mass matrix $M$, Coriolis matrix $C$ and gravity vector $N$ can be computed



# An Experimental Setup for Teleopera(on

## Decoupling the Dynamics

- Joint space dynamic equa(on: $M\ddot{q} + C\dot{q} + N = \tau$
- Transforma(on into Cartesian space:

$$M_c\ddot{p} + C_c\dot{p} + N_c = F$$

- Define desired mass matrix:

$$\overline{M}_c = \begin{bmatrix} m_x & 0 & 0 \\ 0 & m_y & 0 \\ 0 & 0 & m_z \end{bmatrix}$$

- Decouple dynamics:

$$\overline{M}_c\ddot{p} + \underbrace{\otimes_c M \ddot{p}_c + C \dot{p}_c + N}_{F_d} = F$$

$$\Downarrow \quad F = F_c + F_d$$

$$\overline{M}_c\ddot{p} = F_c$$

$$p = [x, y, z]^T$$

$$\dot{q} = J^{-1}\dot{p}$$

$$\ddot{q} = J^{-1}\ddot{p} + \tfrac{d}{dt}(J^{-1})\dot{p}$$

$$M_c = J^{-T}MJ^{-1}$$

$$C_c = J^{-T}\left(CJ^{-1} + M\tfrac{d}{dt}(J^{-1})\right)$$

$$N_c = J^{-T}N$$

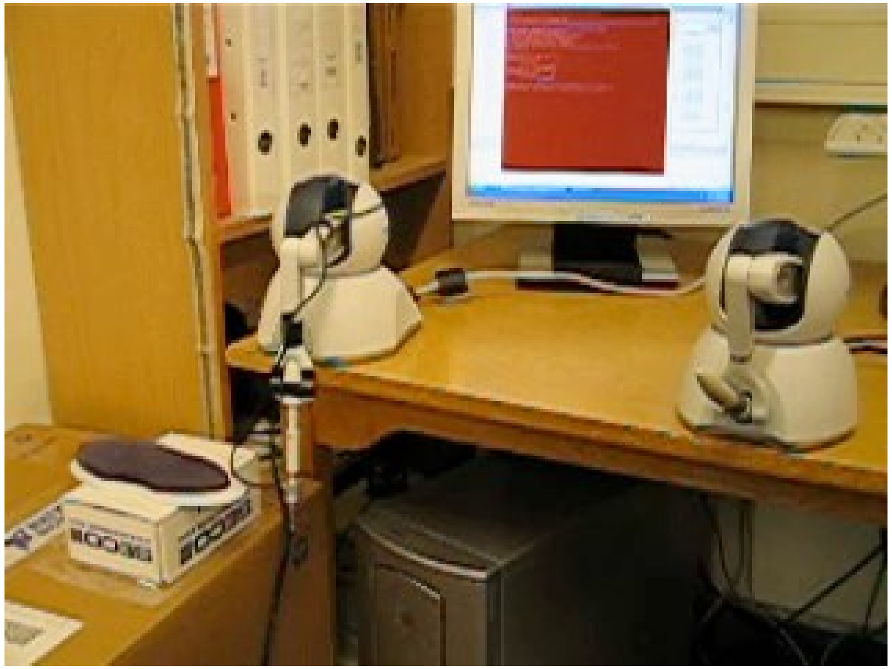
$$F = J^{-T}\tau$$

$$\otimes M_c = M_c - \overline{M}_c$$

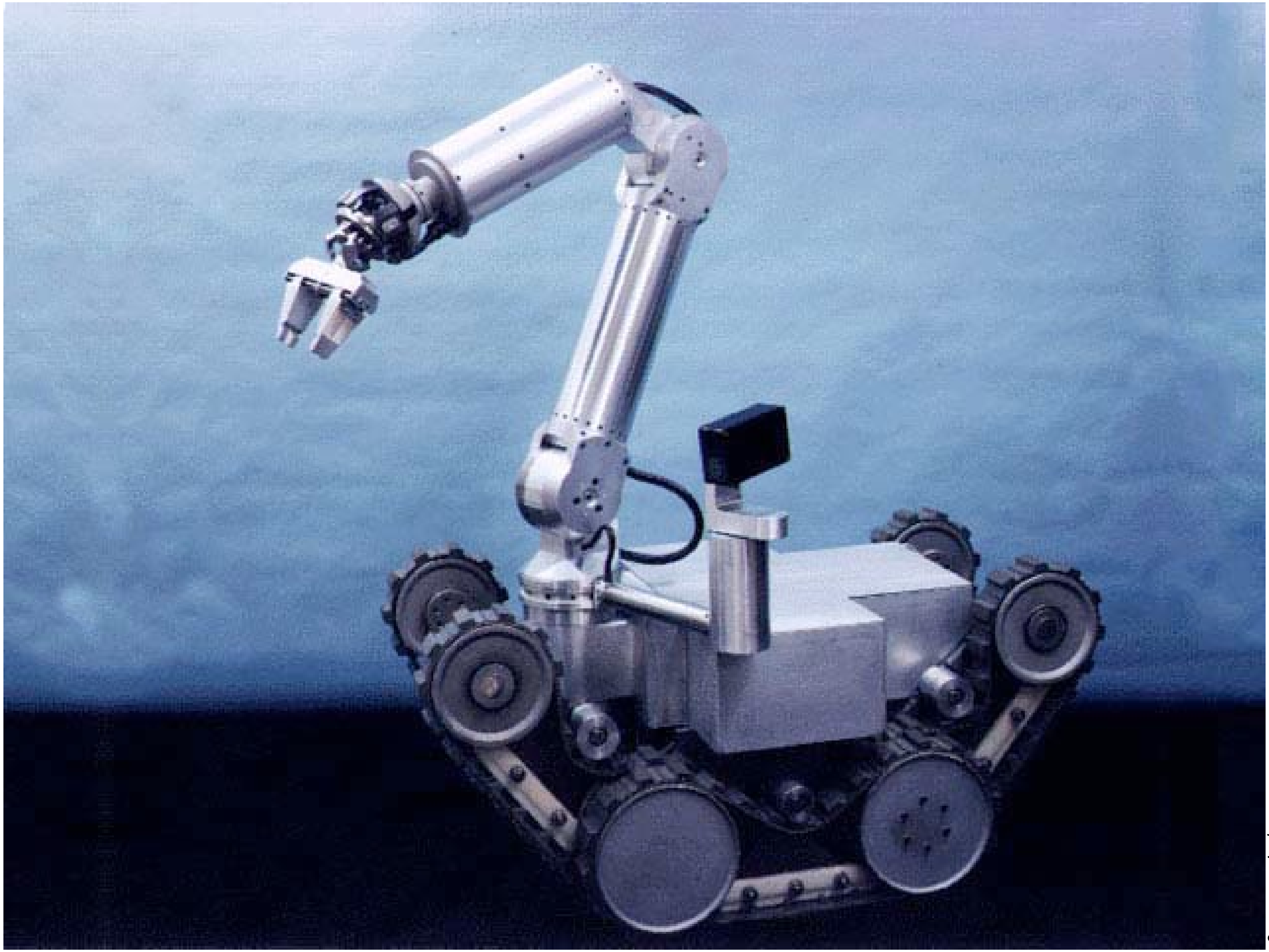
$$F_c = [f_x, f_y, f_z]^T$$

# An Experimental Setup for Teleopera(on

## Video Examples

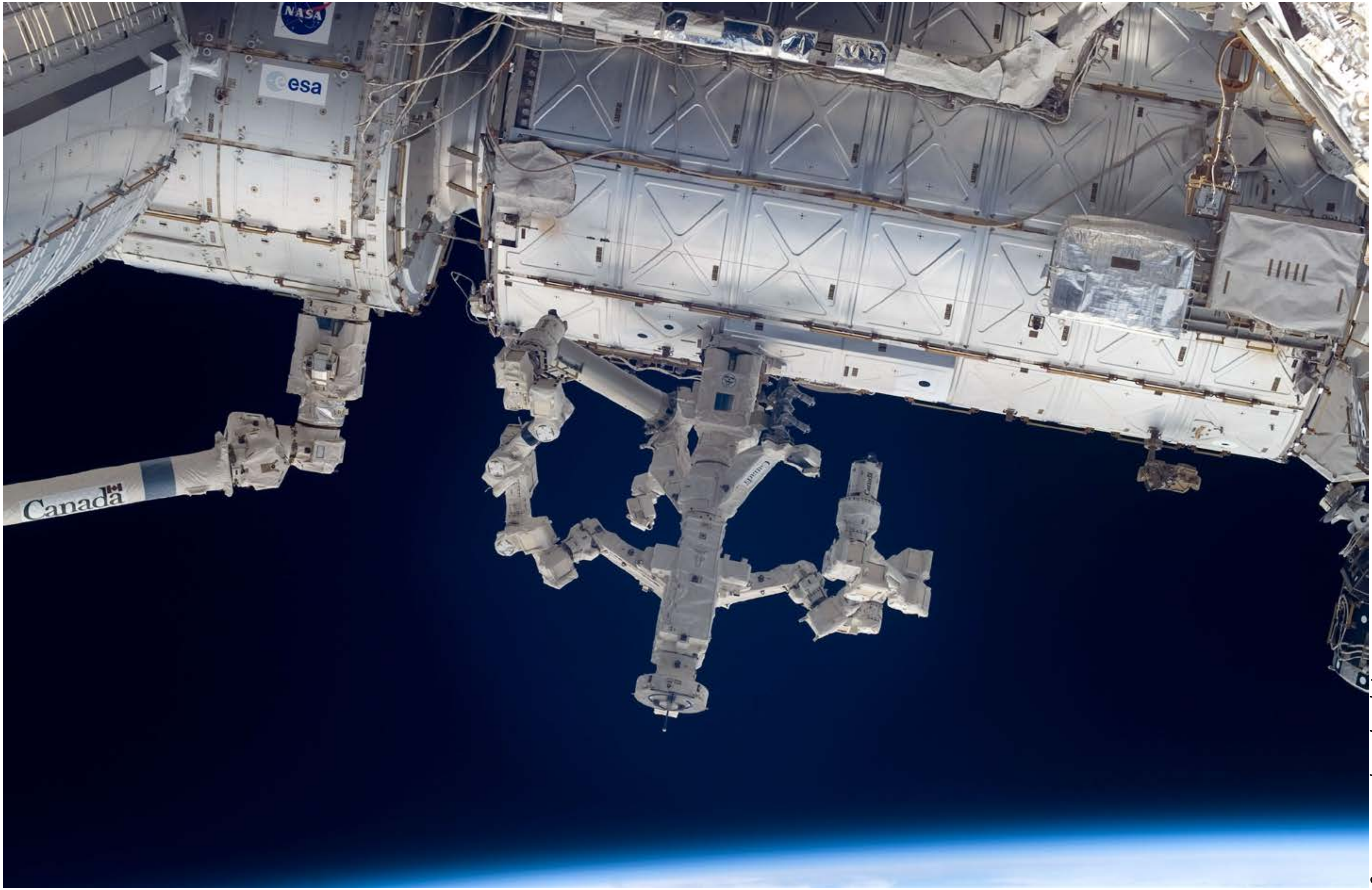


Source: Argonne Na)onal Labs public info office



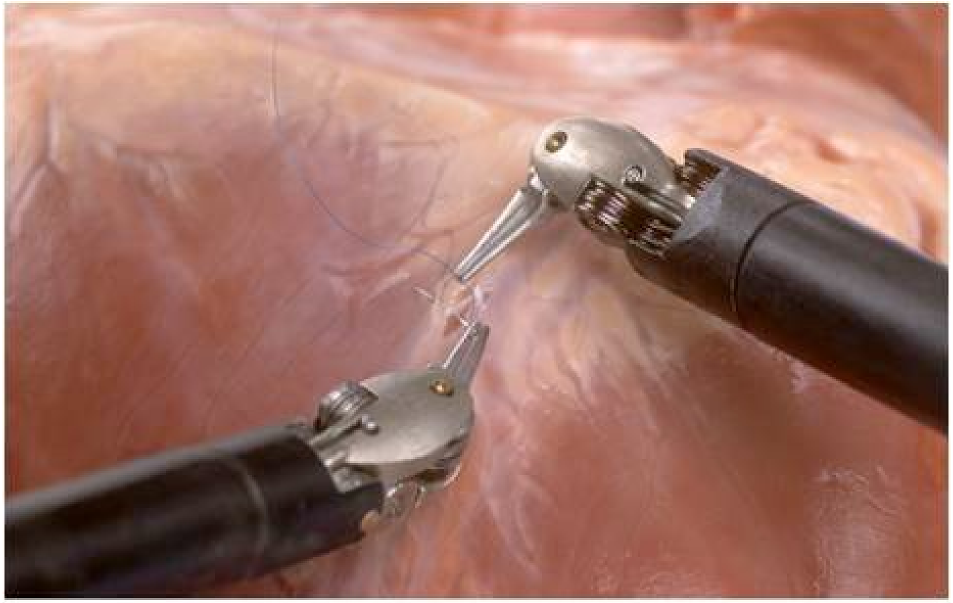
Source: ranier.hq.nasa.gov


Source: robot.kut.ac.kr



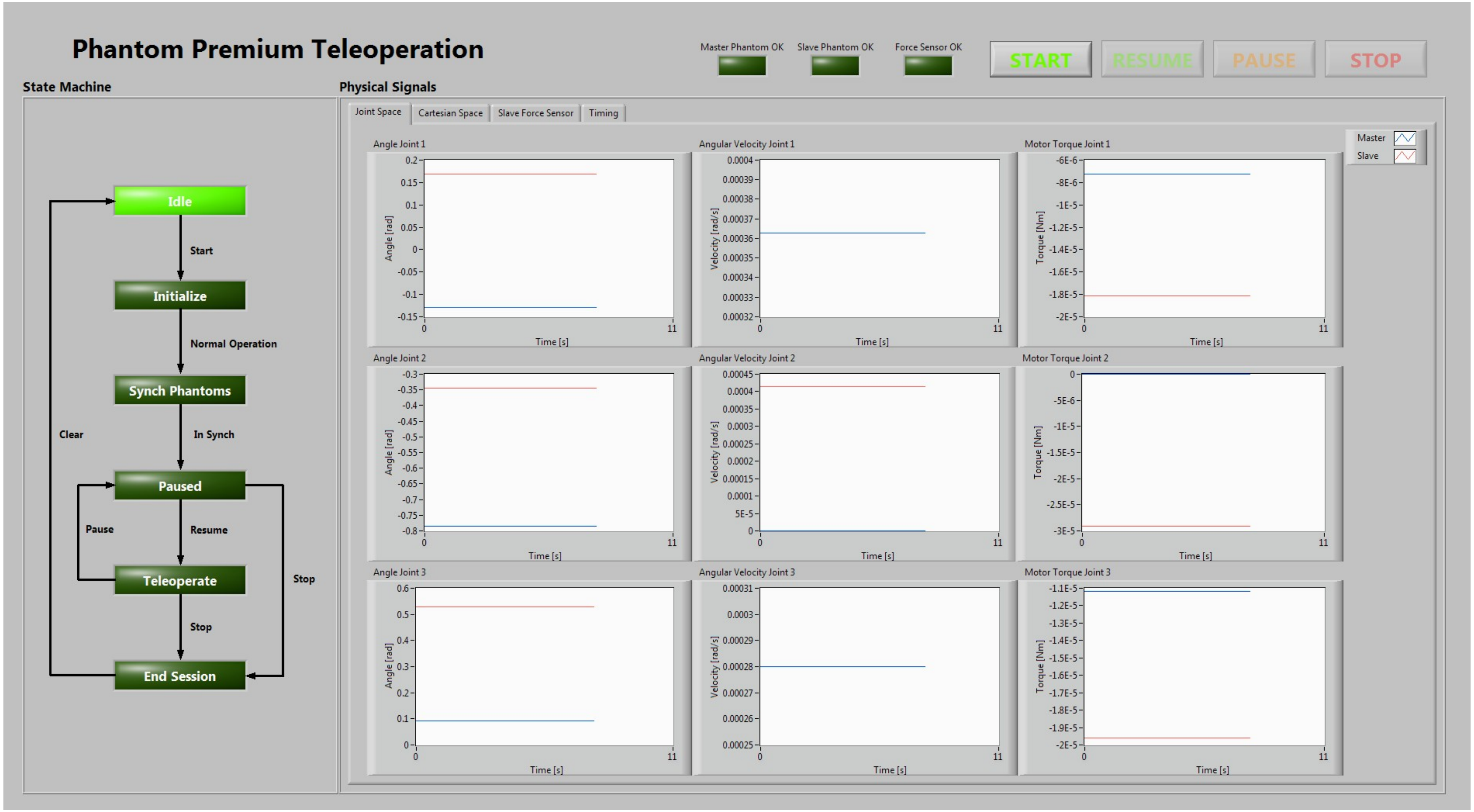

*Source: www.phys.ncku.edu.tw*

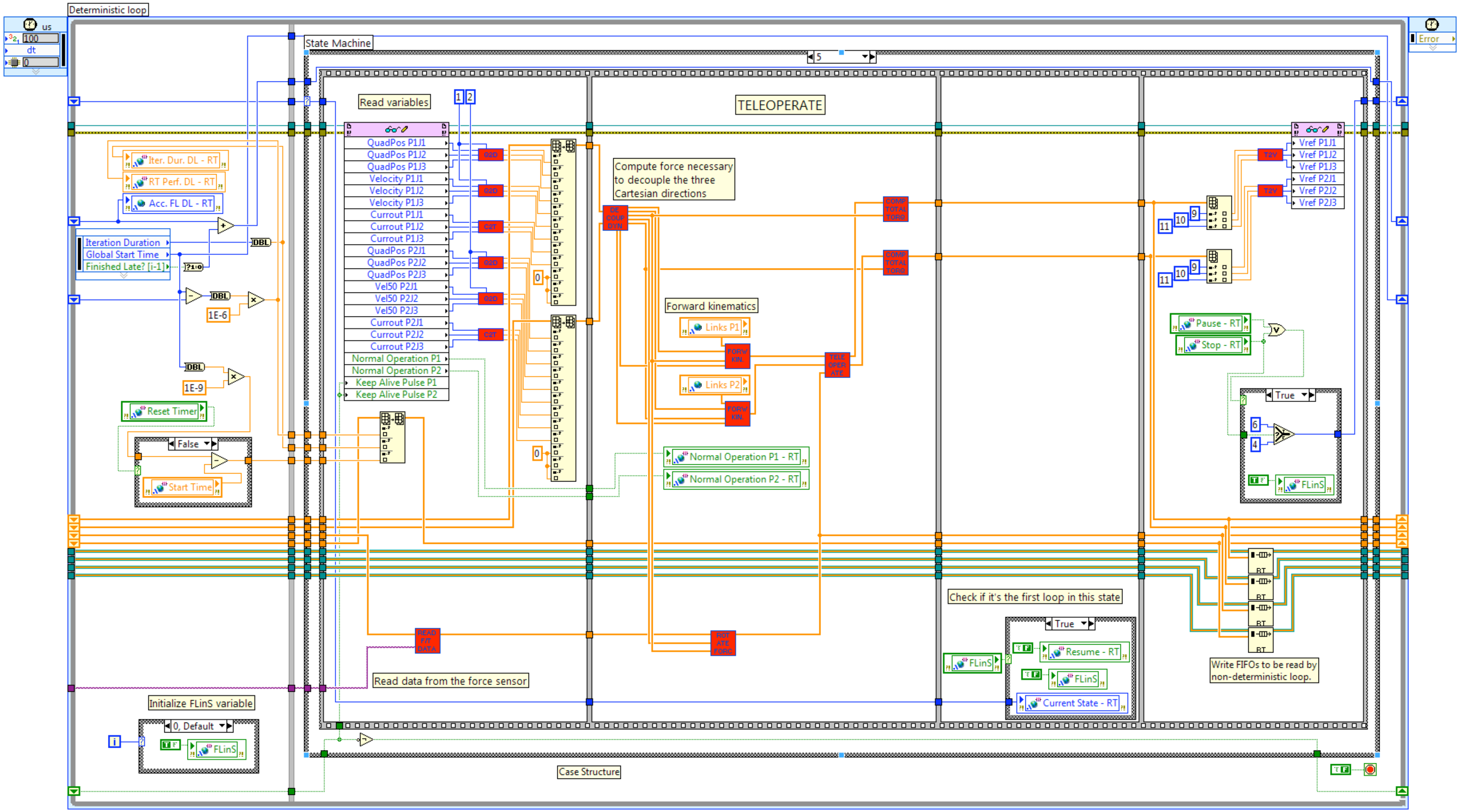

Source: www.emeraldinsight.com



Source: www.intui)vesurgical.com

Source: www.kotaku.com


Phantom Premium Teleoperation
Master Phantom OK
Slave Phantom OK
Force Sensor OK
START
RESUME
PAUSE
STOP
State Machine
Idle
Start
Initialize
Normal Operation
Synch Phantoms
In Synch
Clear
Paused
Pause
Resume
Teleoperate
Stop
Stop
End Session
Physical Signals
Joint Space
Cartesian Space
Slave Force Sensor
Timing
Master
Slave
Angle Joint 1
Angular Velocity Joint 1
Motor Torque Joint 1
Angle Joint 2
Angular Velocity Joint 2
Motor Torque Joint 2
Angle Joint 3
Angular Velocity Joint 3
Motor Torque Joint 3
Angle [rad]
Velocity [rad/s]
Torque [Nm]
Time [s]


Deterministic loop
us
dt
State Machine
5
Read variables
TELEOPERATE
QuadPos P1J1
QuadPos P1J2
QuadPos P1J3
Velocity P1J1
Velocity P1J2
Velocity P1J3
Currout P1J1
Currout P1J2
Currout P1J3
QuadPos P2J1
QuadPos P2J2
QuadPos P2J3
Vel50 P2J1
Vel50 P2J2
Vel50 P2J3
Currout P2J1
Currout P2J2
Currout P2J3
Normal Operation P1
Normal Operation P2
Keep Alive Pulse P1
Keep Alive Pulse P2
Iter. Dur. DL - RT
RT Perf. DL - RT
Acc. FL DL - RT
Iteration Duration
Global Start Time
Finished Late? [i-1]
1E-6
1E-9
Reset Timer
False
Start Time
Compute force necessary
to decouple the three
Cartesian directions
Forward kinematics
Links P1
Links P2
Normal Operation P1 - RT
Normal Operation P2 - RT
Read data from the force sensor
Initialize FLinS variable
0, Default
FLinS
Case Structure
Check if it's the first loop in this state
True
Resume - RT
Current State - RT
Vref P1J1
Vref P1J2
Vref P1J3
Vref P2J1
Vref P2J2
Vref P2J3
Pause - RT
Stop - RT
Write FIFOs to be read by
non-deterministic loop.
Error