From Equations to Embodiment – 3 Case Studies

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November 30, 2011

IIT-M, NaCoMM 2011

Ackowledgement

- Dr. R. Ranganath @ ISAC-ISRO
- Dr. Sandipan Bandyopadhyay @IIT-M
- Dr. M Ramesh, Consulting Laparoscopic Surgeon, A V Hospital, Bangalore
- V C Ravi @CAIR
- Sreenivasan S
- Piyush Goel
- Deepak C
- GTTC and Mahant Tool Room, Bangalore
- Funding Agencies – SBMT and ISRO

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Stewart platform based Force-torque Sensor

Improved Laparoscopic Surgical Tool

Hyper-redundant Manipulator

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Introduction

One of the first Ph D in India in the area of kinematics and mechanisms (1969)

Translated *Machine Elements: Design and Calculation in Mechanical Engineering* by Gustav Niemann from German to English (with M.A. Parameswaran, G.V.N. Rayudu)

Prof. K Lakshminarayana
Dept. of Mechanical Engineering
IIT Madras
(Source: K Eswar)

Well known for obtaining a condition for form closure – used extensively in initial research on grasping

Introduction

Mechanisms and machines are used everywhere!

Analysis – Modeling, Equations & Computations
→ Kinematics
→ Dynamics
→ …

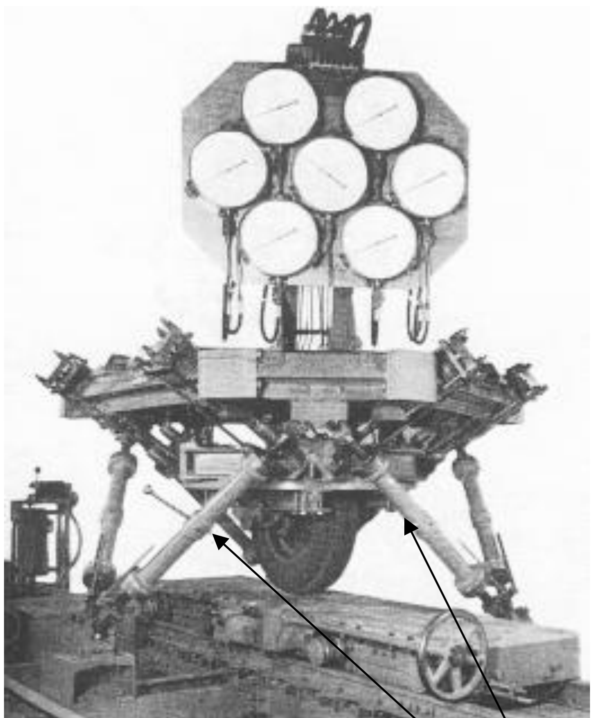
Design – Synthesis
→ Embodiment
→ Prototyping
→ ….

Both are equally important!

3 Case Studies – Equations to Embodiment

Case 1: Stewart Platform based Force-torque Sensor

Gough- Stewart Platform



→ First used as a tire-testing machine in UK

→ Six actuated extendable legs -- 6 DOF

Linear motion along **X, Y** and **Z**
Rotational motion about **X, Y** and **Z**

Also known as **Heave, Surge, Sway**
&
Roll, Pitch and Yaw

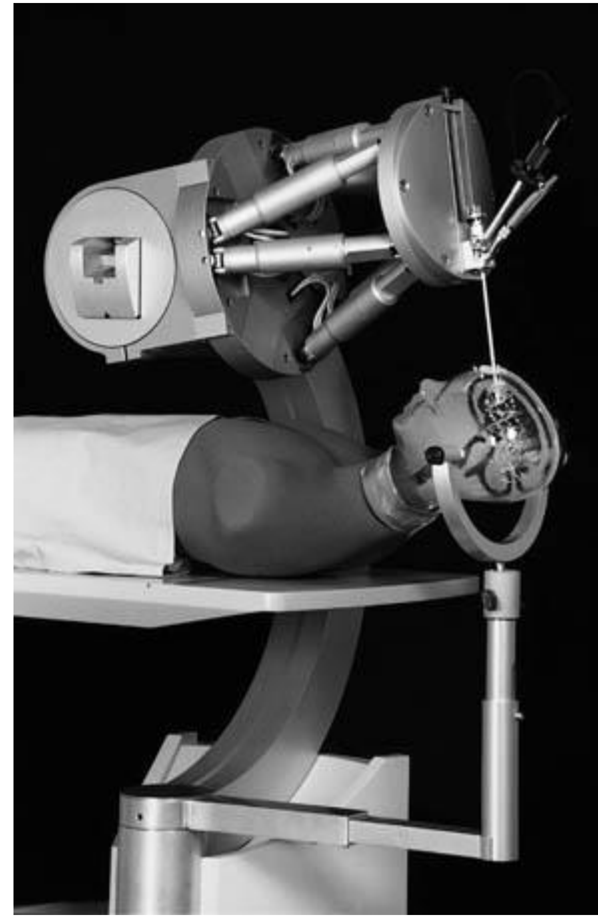
Stewart 1965

Extendable `legs’

Modern uses of Gough - Stewart platforms

Industrial – material handling

Micro-motion



Robotic surgery

Industrial – manufacturing

Precise alignment of mirrors

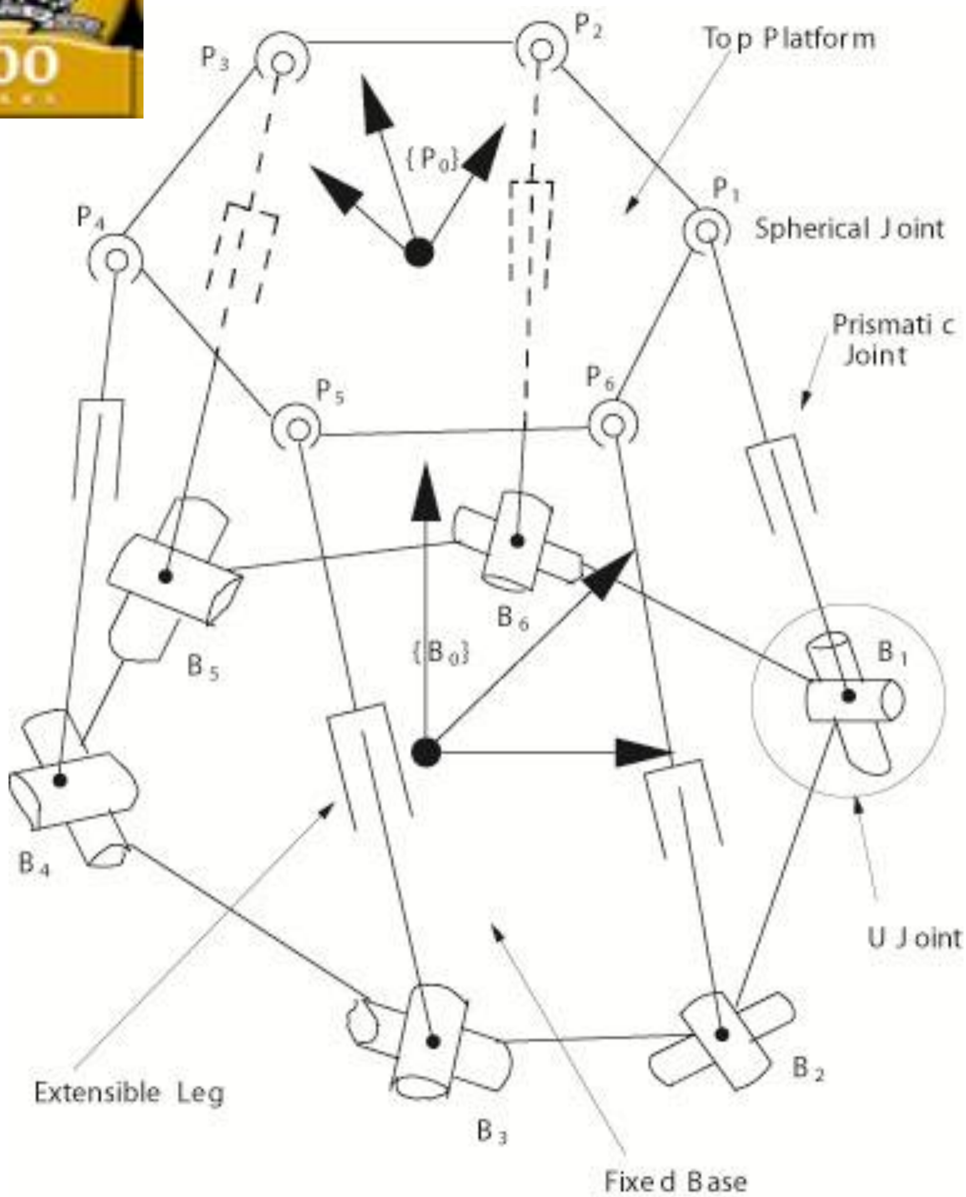
Gough-Stewart Platform

Cabin with audio-visual display

Flight Simulators

Legs of Gough-Stewart platform

Gough- Stewart Platform



→Moving Top Platform
→Fixed Base

6 actuated joints

→Actuating joints in a coordinated manner results in motion of top platform

Motion Simulation

Simulations done using ADAMS

Individual motions and combined motion of a Gough-Stewart platform -- simulations

Gough-Stewart Platform as a Sensor

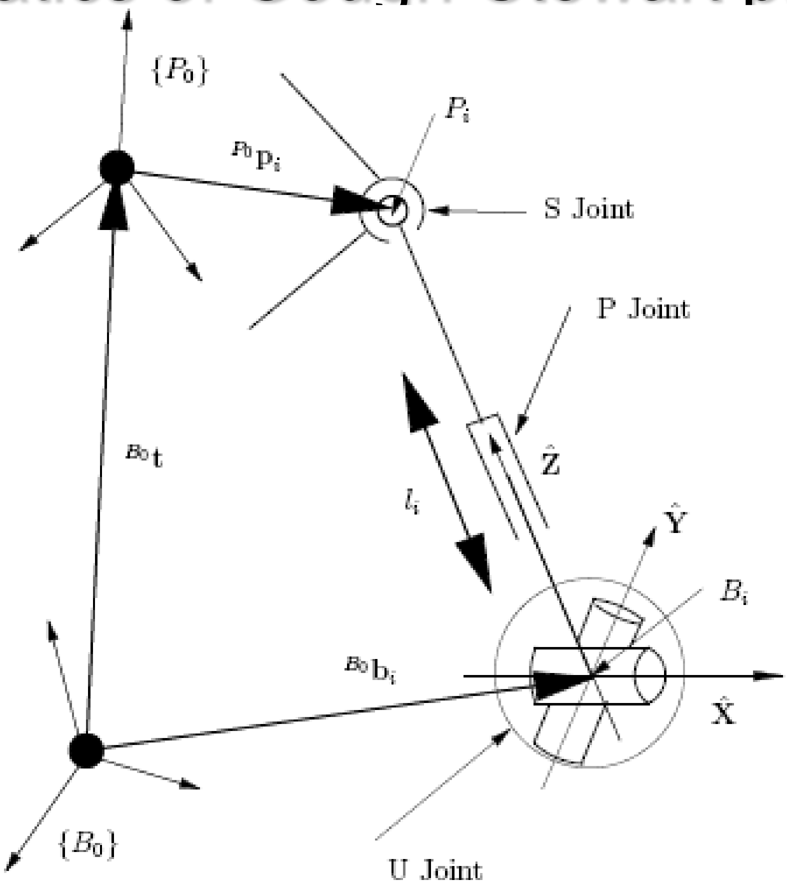
- Gough-Stewart platform as a 6 –axis force torque sensor

  → Actuators are locked – 0 degrees of freedom

  → Instead of applying force at actuators/cylinders, strain gauge based sensors put there to measure strains

  → Externally applied force-moment at the top platform can be sensed at the legs

Statics of Gough-Stewart platform



A leg of a Stewart platform

$$^{B_0}\mathbf{S}_i = {}^{B_0}_{P_0}[R]\,{}^{P_0}\mathbf{p}_i + {}^{B_0}\mathbf{t} - {}^{B_0}\mathbf{b}_i$$

$$^{B_0}\mathbf{s}_i = \frac{^{B_0}\mathbf{S}_i}{l_i}$$ ← Unit vector along leg

$$\begin{pmatrix} ^{B_0}\mathbf{F}_{Tool} \\ --- \\ ^{B_0}\mathbf{M}_{Tool} \end{pmatrix} = \begin{bmatrix} \sum_{i=1}^{6} {}^{B_0}\mathbf{s}_i f_i \\ --- \\ \sum_{i=1}^{6} ({}^{B_0}\mathbf{b}_i \times {}^{B_0}\mathbf{s}_i) f_i \end{bmatrix}$$

External load – force & moment

$$^{B_0}\mathcal{F}_{Tool} = {}^{B_0}_{Tool}[\ H\ ]\mathbf{f}$$ ← Leg Forces

$$^{B_0}_{Tool}[\ H\ ] = \begin{bmatrix} ^{B_0}\mathbf{s}_1 & ^{B_0}\mathbf{s}_2 & \cdots & ^{B_0}\mathbf{s}_6 \\ --- & --- & --- & --- \\ (^{B_0}\mathbf{b}_1 \times {}^{B_0}\mathbf{s}_1) & (^{B_0}\mathbf{b}_2 \times {}^{B_0}\mathbf{s}_2) & \cdots & (^{B_0}\mathbf{b}_6 \times {}^{B_0}\mathbf{s}_6) \end{bmatrix}$$

Final formula → **f** = inv ([H])(F;M)

6 Component Force-Torque Sensor

- Basic formula **f** = inv ([H])(F;M)

  → Matrix [H] depends on chosen geometry

  → (F;M) -- 6 components of externally applied force and moments

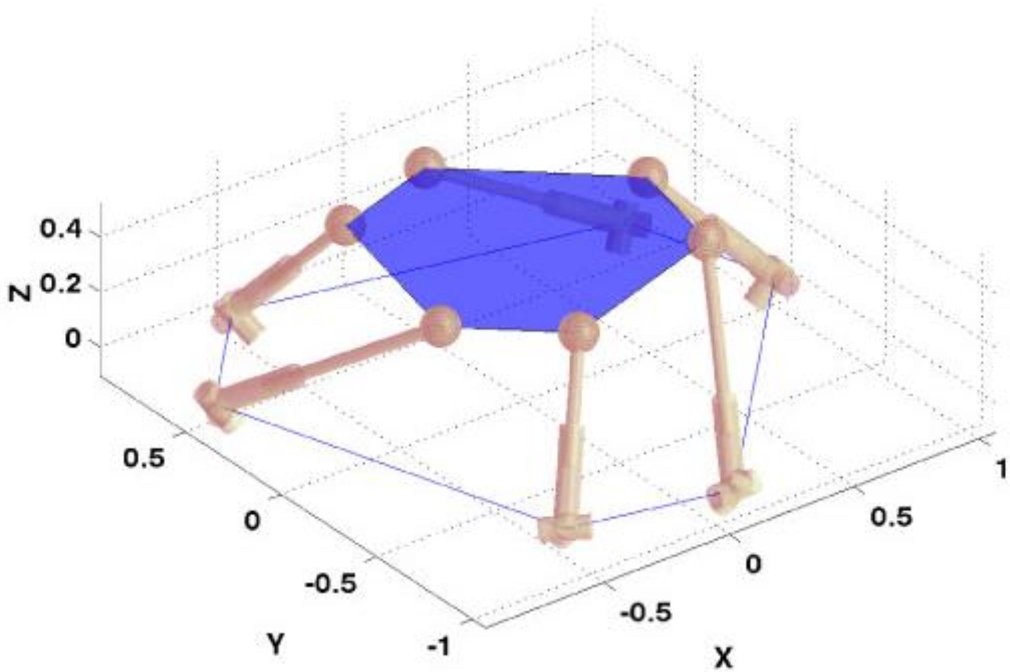
  → f – axial forces in the 6 legs
- If [H] is isotropic, all components are equally sensitive
- If [H] is singular, certain components will be amplified ``mechanically"

Isotropic Configuration

Det [H]≠ 0

→Eigenvalues of [H] are ``equal”

→All directions are ``equivalent”



Force-moment isotropic configuration of a Gough-Stewart platform

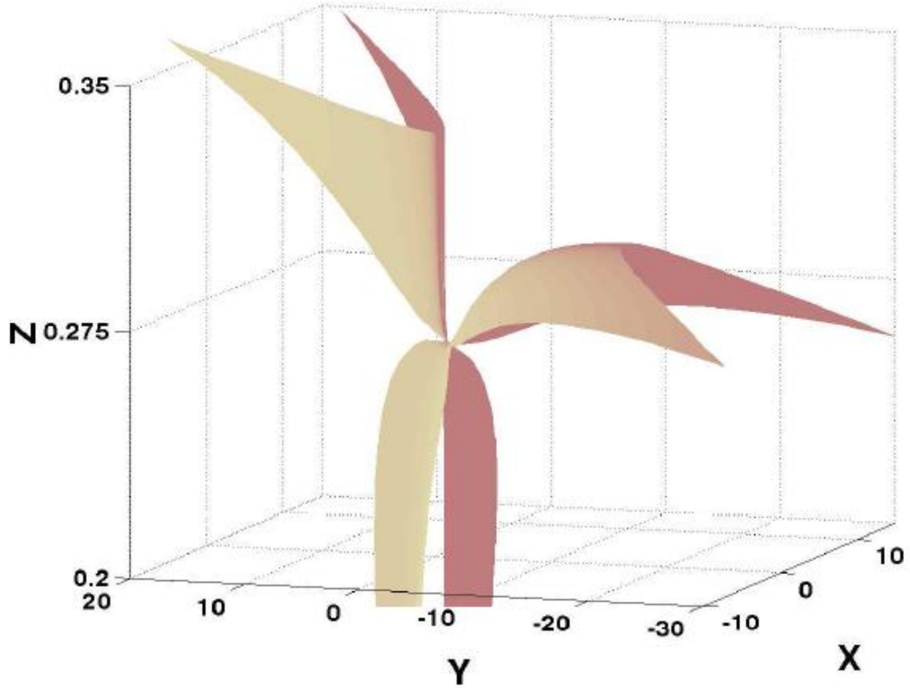
Bandyopadhyay & AG MMT 08

Singularities

Two kinds of Singularities

→ Loss of degree of freedom from 6 to 5 or less

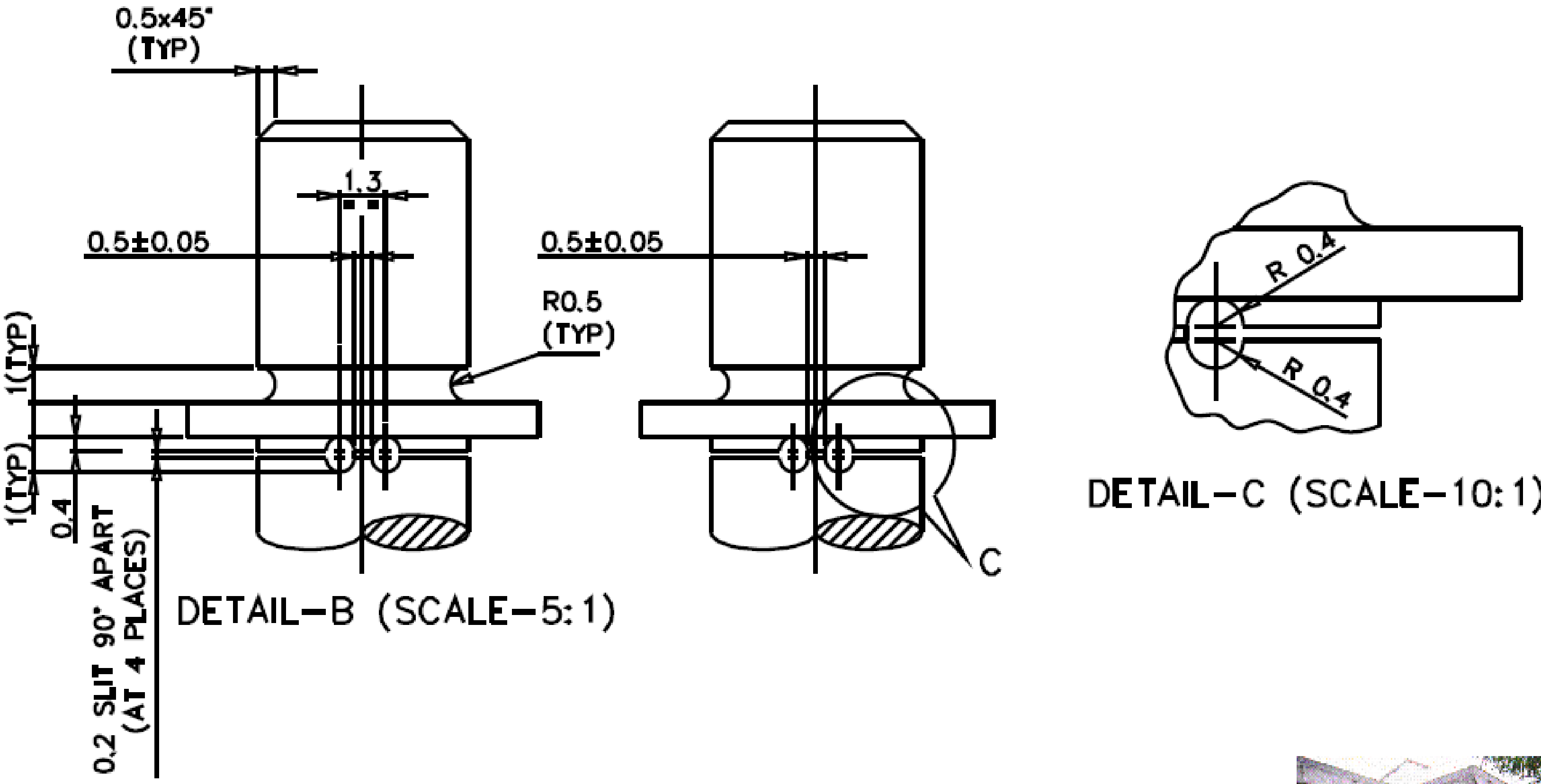
→Gain of degree of freedom – with ``locked'' actuators, the top platform can move!! → Det [H] = 0



Singularity manifold at a given orientation of top platform

Bandyopadhyay & AG MMT 06

6 Component Force-Torque Sensor



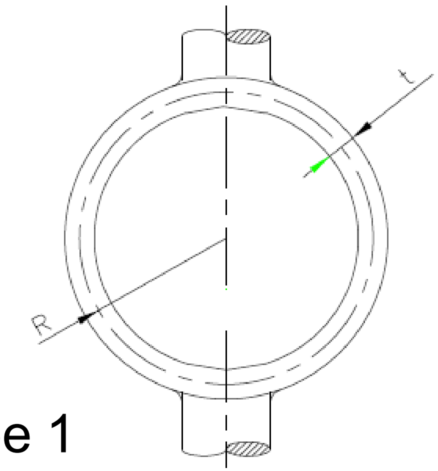
Flexible hinges (instead of joints) to overcome friction & hysterisis

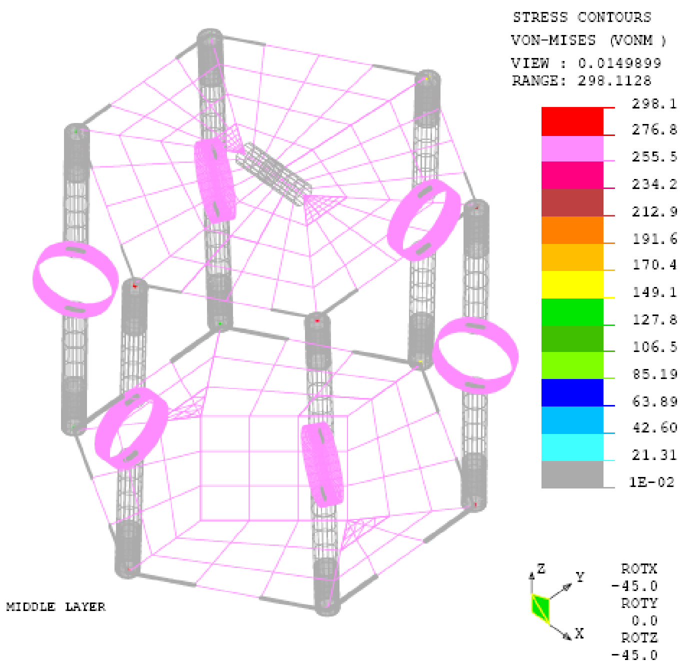
Ranganath et al. MMT 04

- Prototype 1 -- ISRO

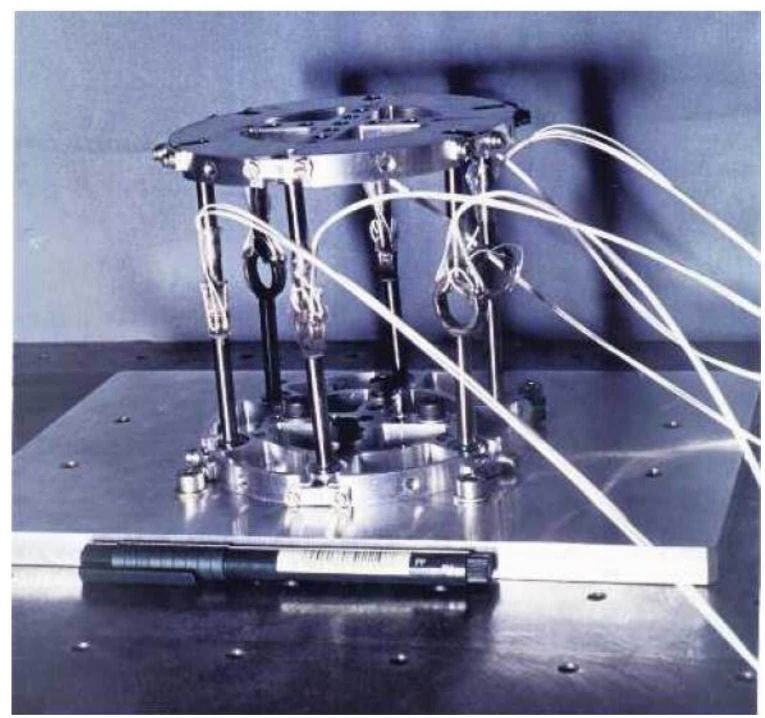
FEA in NISA

Force sensing
ring element in leg



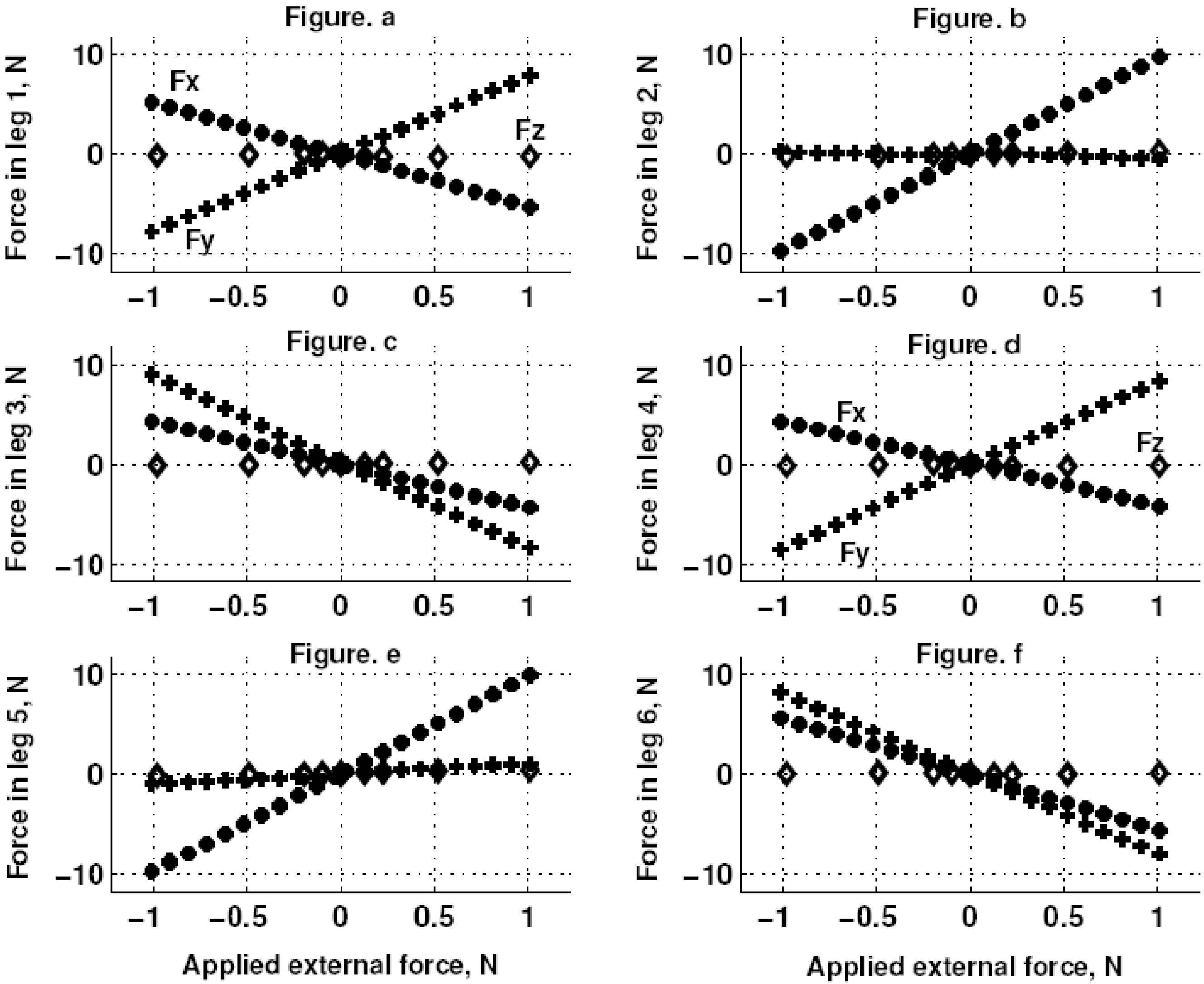


Prototype 1



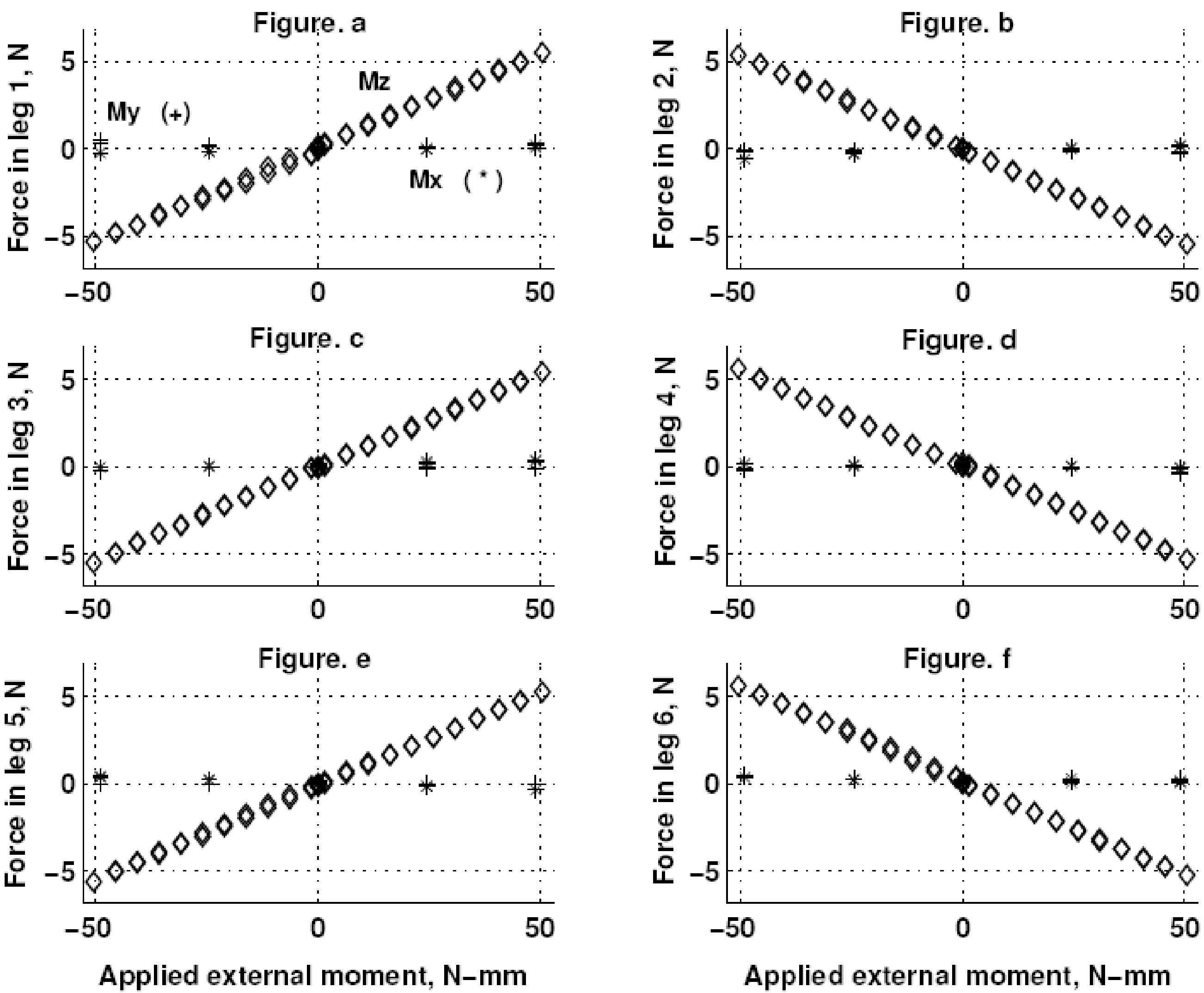
Ranganath et al. MMT 04

Sample experimental results



Shows enhanced sensitivity for Fx, and Fy components

Ranganath et al. MMT 04

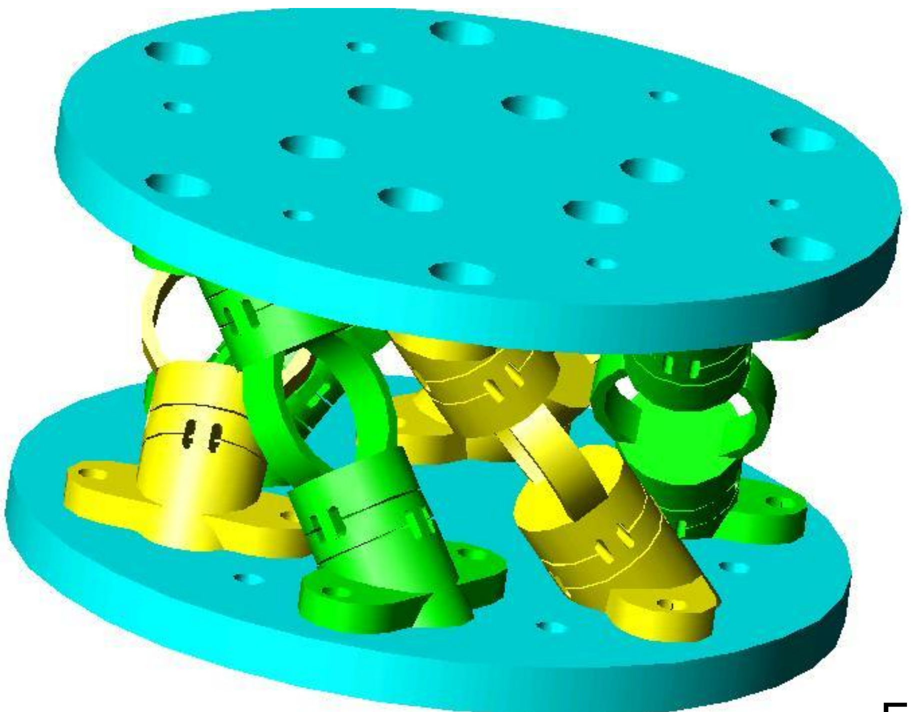


Sample experimental results

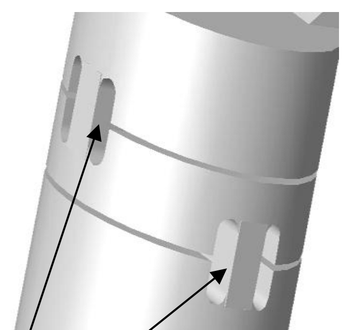
Shows enhanced sensitivity for Mz component

Ranganath et al. MMT 04

- Prototype 2 – sensitive to Mx, My & Mz



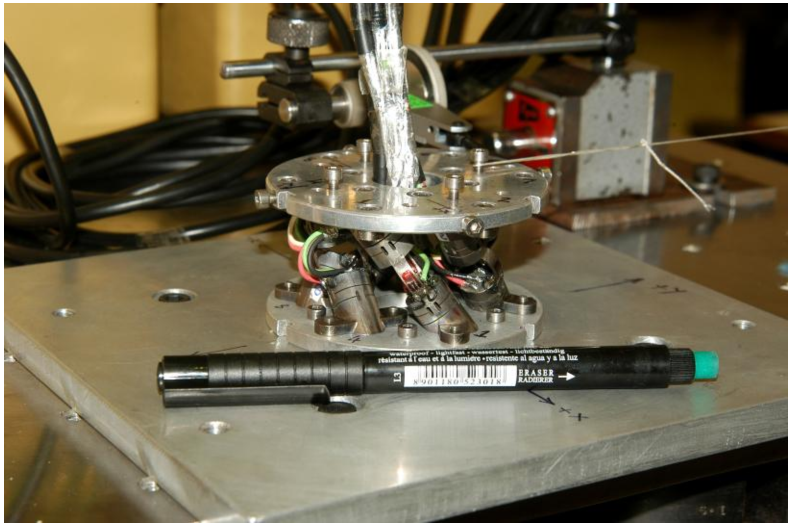
CAD model of sensor



Flexible hinge – 2 DOF

CAD model of a leg with sensing ring

Prototype 2



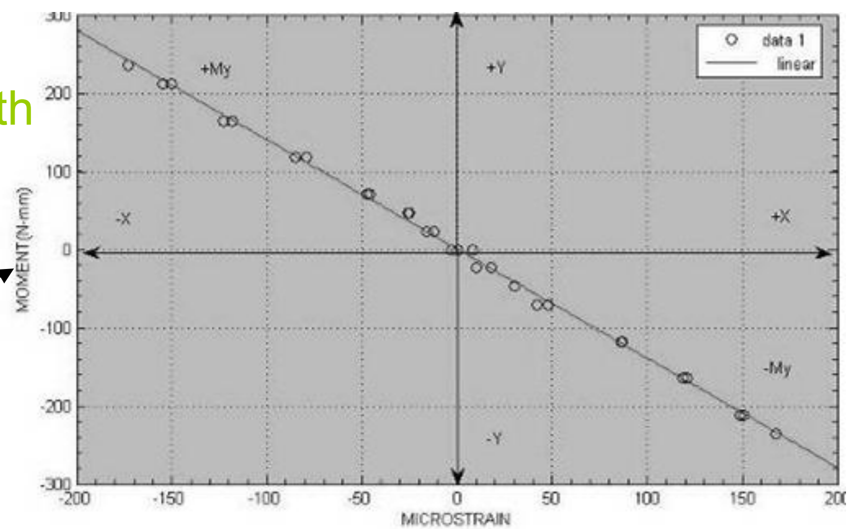
Six component force-torque sensor with enhanced sensitivity to moments.

Measure forces up to 50 N in X and Y and 200 N in Z direction with sensitivity of 0.5N

Measure moments up to10,000 N-mm with sensitivity of 50 N-mm

Stewart in a near-singular configuration with flexible hinges

Experimental test results for My



Plot of strain (leg1) vs My

http://www.mecheng.iisc.ernet.in/~asitava/NaCoMM-2007-061.pdf

Summary of Case 1

Gough - Stewart platform, a versatile device
– used in wide range of tasks.

Extensively used as motion platform
– flight simulators in aerospace industry.

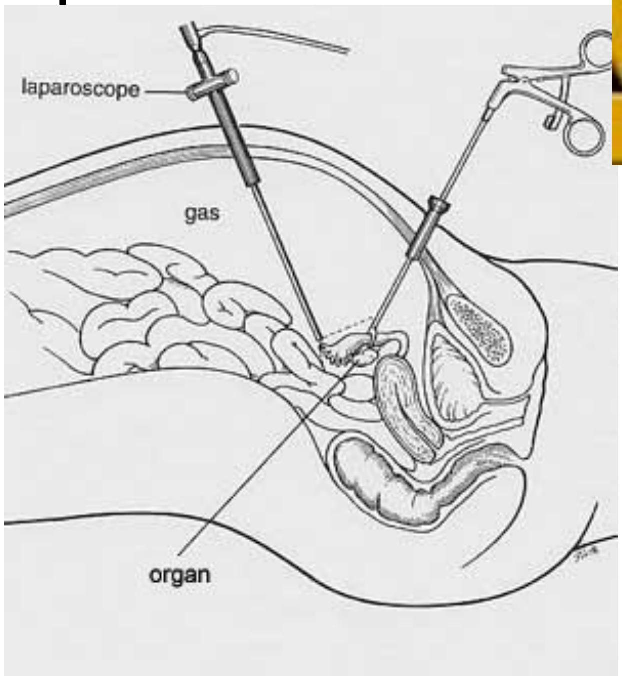
Gough - Stewart platform as 6 component force-torque sensor.

Kinematics and statics equations.

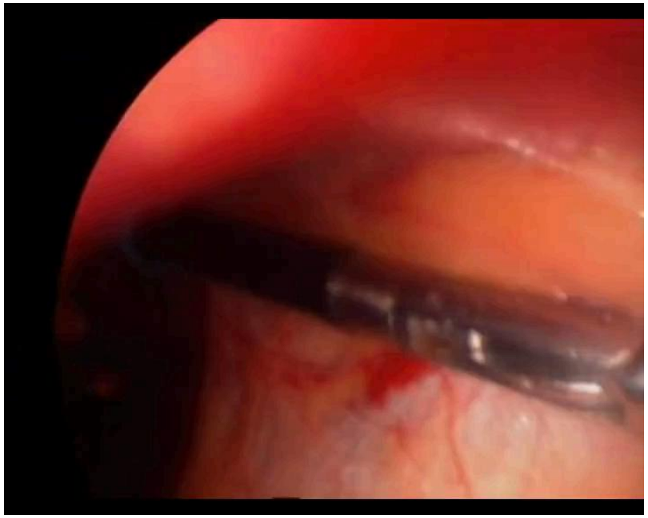
Two prototypes, calibration, testing & refinement.

Case 2: Improved Laparoscopic Surgical Tool

- Laparoscopic Surgery
  - A type of Minimally Invasive Surgery
  - Advantage
    - Reduces trauma and blood loss
    - Accelerated recovery
  - Disadvantage
    - Difficult to perform – Lack of dexterity
  - Tools used for laparoscopic surgery
    - Trocar
    - Endoscope
    - Surgical tools



Movie clip – Hernia surgery



Figures: www.nemc.org/Surgery/html/bariatric/surg_025.jpg & Surgery performed at BEST, Bangalore

Existing Laparoscopic Surgical Tool

Performs operating tasks like Grasping, Cutting, Suturing

A typical hand operated laparoscopic surgery tool

Motions of the tool – 4 DOF

- Roll about axis of slender rod
- Sliding motion between tool and trocar
- Pitch and Yaw (about the trocar)
- Actuation of end-effector

- Approach ONLY from direction of incision
- Lack of dexterity

www.northshorelij.com/...
/Image53-2f_r1_c2.jpg

Existing Laparoscopic Surgical Tool

Limitations of present surgical tools

→ Limited access,

→ Inability to avoid obstacles,

→ Difficulty in performing complex operating tasks

→ Increase dexterity by adding one or more DOF

Other Limitations

- Lack of sensing of Force and Temperature
  → MEMS based sensors
- Lack of depth perception – 3D Vision
- Lack of a user interface
  → Geometric, FEA, Modeling

The *da Vinci*™ Surgical System
(*©2006 Intuitive Surgical, Inc.*)
Image: www.urologyclinics.com/robotic.html

Existing Tools with Enhanced Dexterity

- Patents based on
  - Cables
    - US Patent US5350391 (1994)
    - US Patent US5454827 (1995)
    - US Patent US6554844 (2003)
    - US Patent US6991627 B2 (2006)
  - Linkages
    - US Patent US5860995 (1999)
  - Gears
    - US Patent US7043338 B2 (2006)

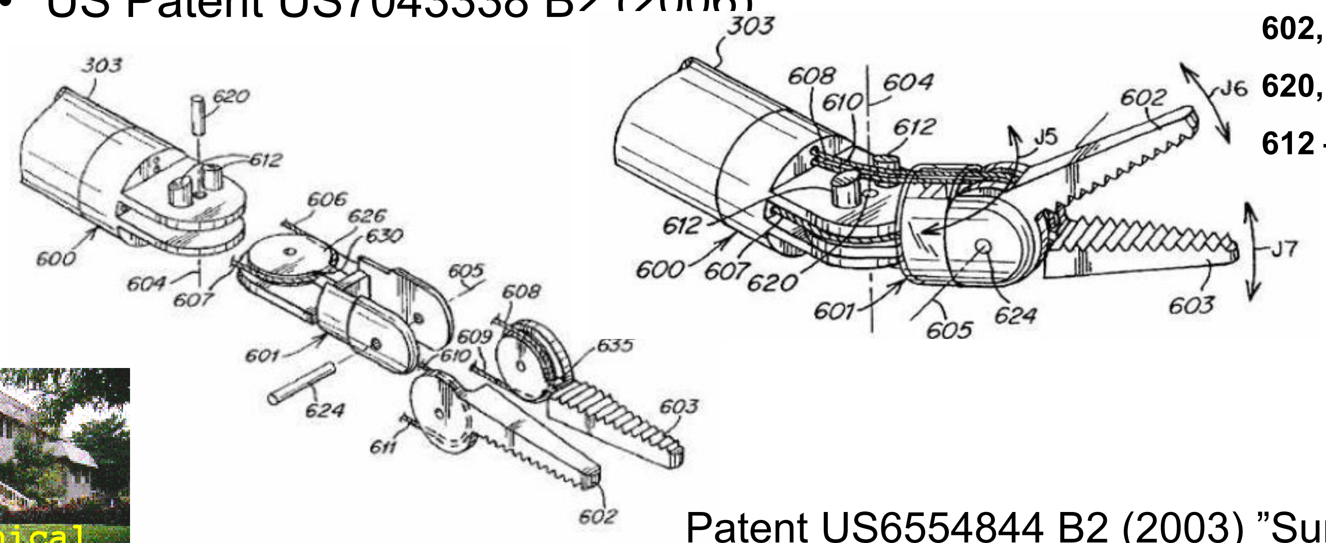
606 – Cable for Articulation

608 – Cable for Actuation

602, 603 – Jaws

620, 624 – Pins

612 – Guides



Patent US6554844 B2 (2003) "Surgical Instrument"

Some Existing Examples

Surgical Innovations
http://www.surginno.com/logiflex.html

Close up view of Endo-flex

Lapfinger – Microline Surgical, Inc
http://www.microlinesurgical.com/products/lapfinger-animation/

SILS^{TM} Hand Instruments

Covidien, UK

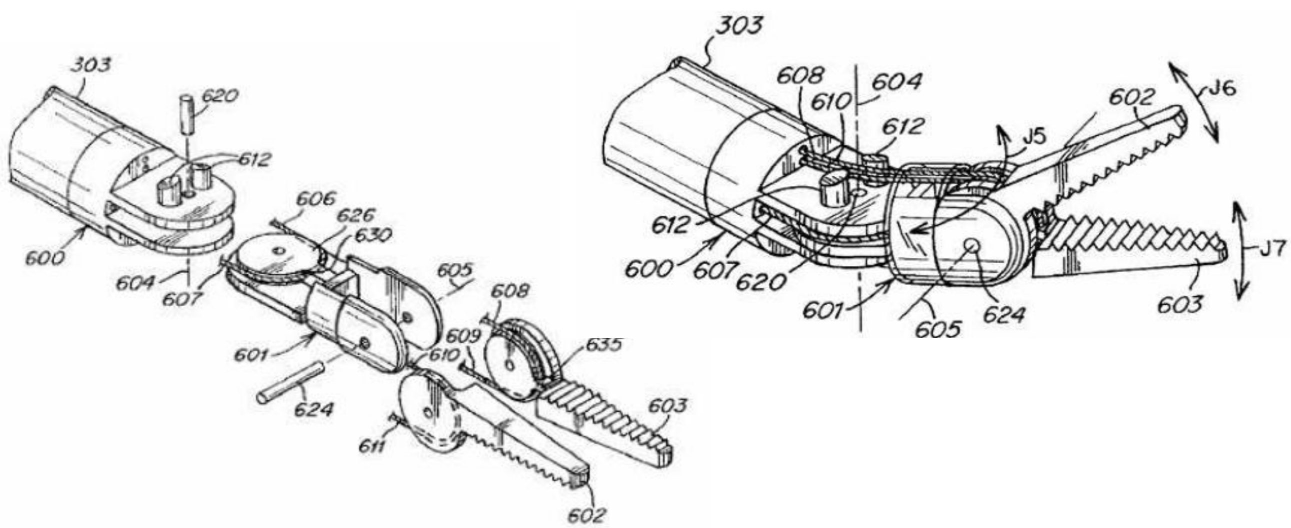
Cable driven – loss of force feedback

Some Existing Dexterous Laparoscopic Tools

Surgical Innovations
http://www.surginno.com/logiflex.html

Close up view of Endo-flex

Lapfinger – Microline Surgical, Inc
http://www.microlinesurgical.com/products/lapfinger-animation/



606 – Cable for Articulation

608 – Cable for Actuation

602, 603 – Jaws

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612 – Guides

Patent US6554844 B2 (2003) "Surgical Instrument"

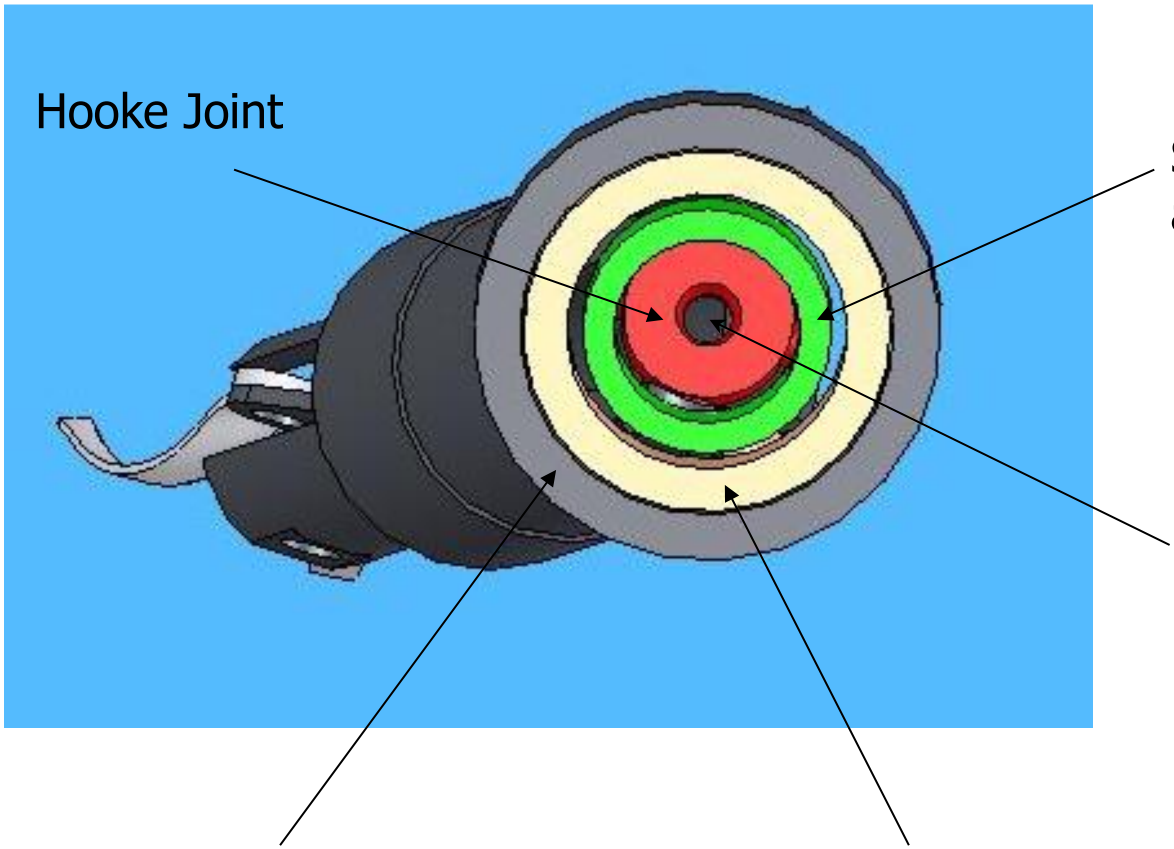
Key Design Considerations

- Existing standards
  - Length of rod/tube of tool: 280 − 300 mm
  - External diameter of rod/tube: 5, 6, 8, 10 mm (limited by dimensions of trocar)
- Other design requirements
  - Bio-compatible (to avoid any kind of infection)
  - Can be sterilized (re-used in some places)
  - Grasping force required 5−10 N*
  - Ergonomic design

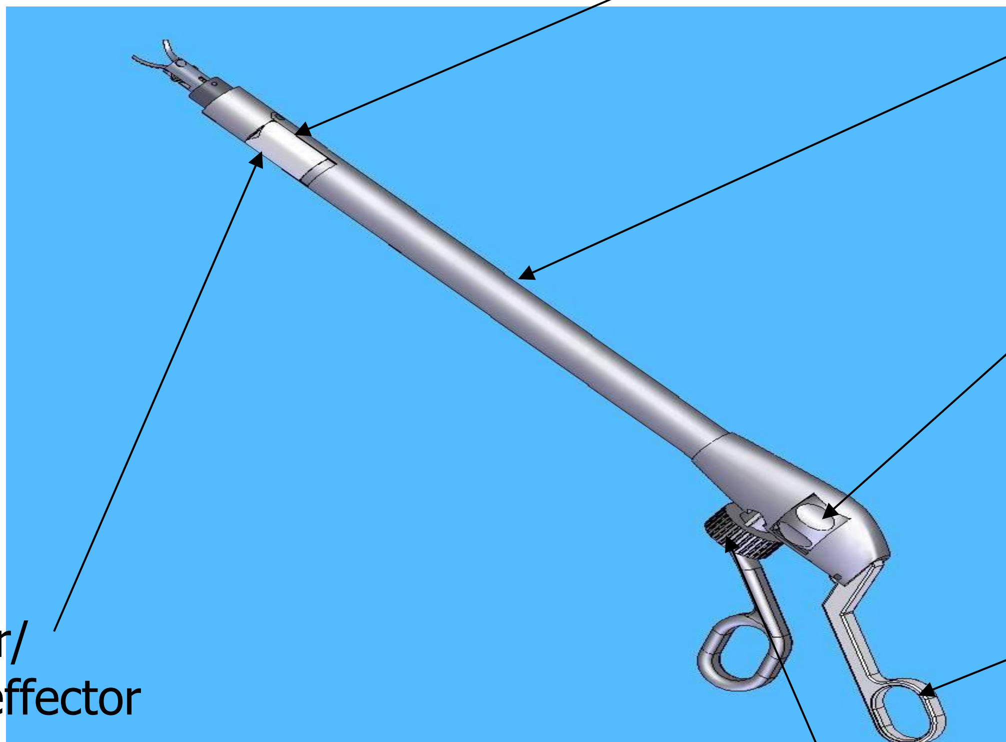
*Venkata, R. C. K (2006) "Design and Characterization of a Novel Hybrid Actuator Using Shape Memory Alloy and D.C Motor for Minimally Invasive Surgery Applications". M. Sc. thesis, Dept. of Electrical Engg. and Computer Science., Case Western Reserve University, Cleveland, Ohio, USA.

Conceptual Design

→ Concentric tubes to transmit 4 DOF motion
→ Implement a ``wrist'' for providing dexterity



CAD Model & Design



Hooke Joint

Outer diameter
10 mm

Roll wheel

End-effector
actuation

Cutter/
End-effector

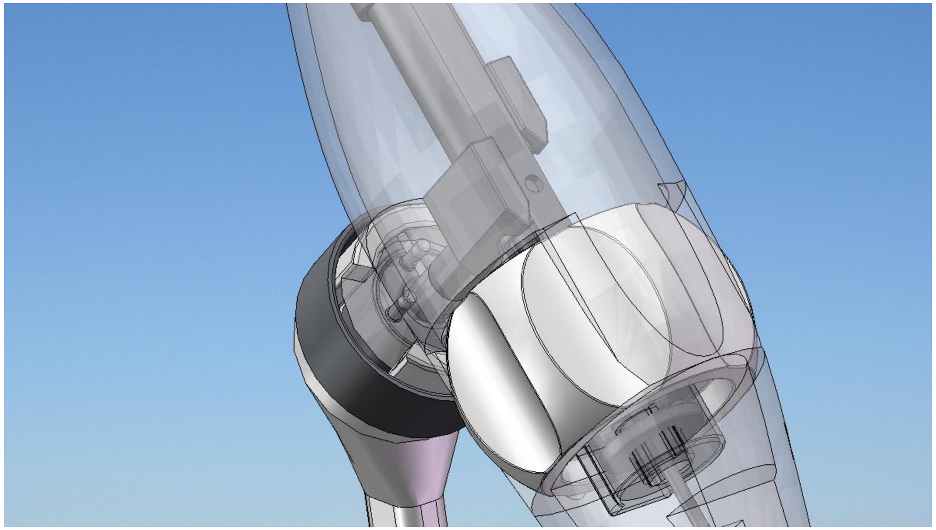
Roller for articulation

Analysis performed using software packages
→ Motion analysis
→ Stress & strength
→ Interference

Animation

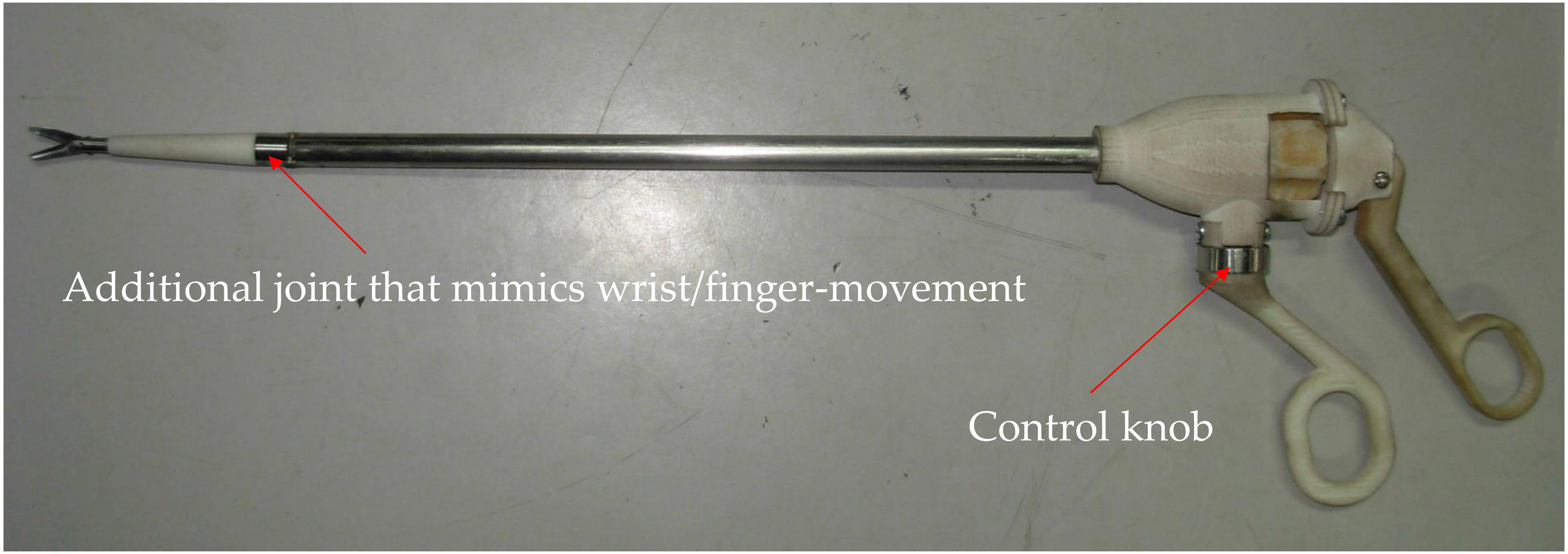
Mechanism
of
operation....
follows

Different arrangement
of actuating mechanisms



Additional articulation DOF

Prototype

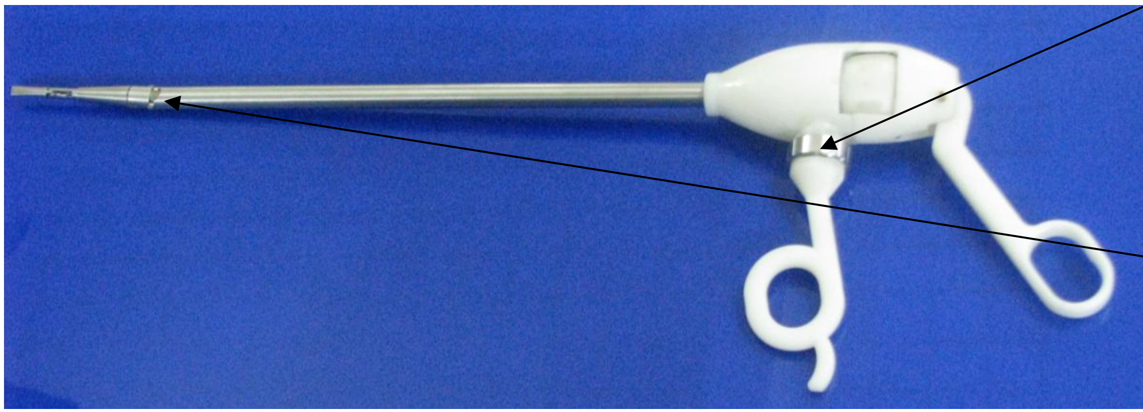


- +/- 30 degrees articulation possible
- Modular design – end-effector can be changed
- Rigid

Patent applied for in India, Piyush Goel, Harihar Kumbhare, M Ramesh & A Ghosal
PCT (WIPO) details http://www.wipo.int/patentscope/search/en/WO2011024200

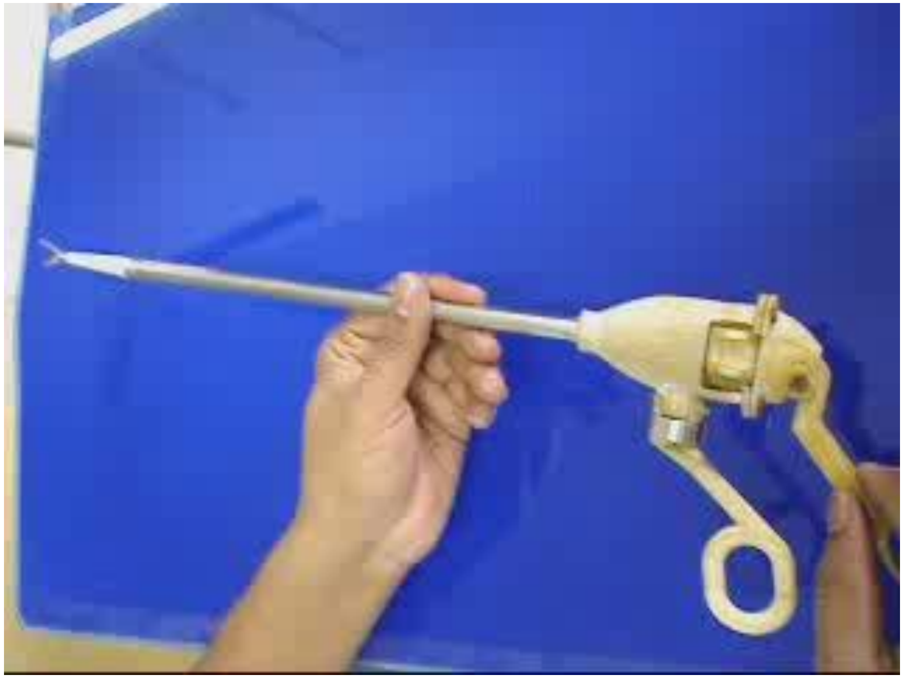
Prototype – Grasper

Actuating mechanism



Additional joint

Videos



Scissor/cutter as end-effector

Grasper as end-effector

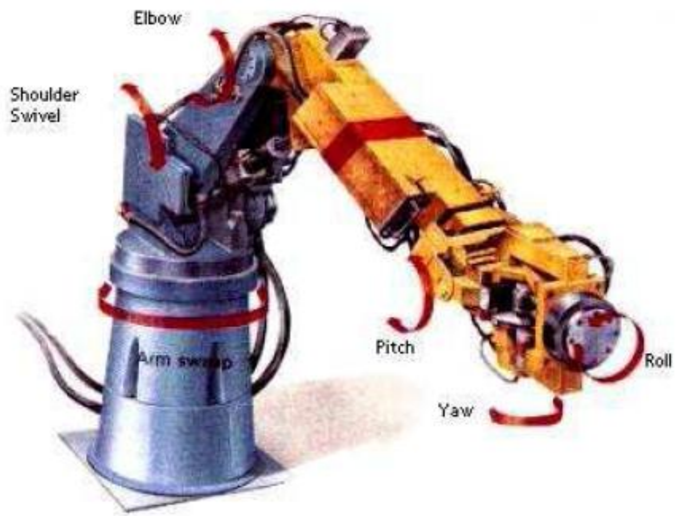
Case 2 -- Work in Progress

- Refinement of prototype
  - → Reduce weight
  - → Eliminate play and backlash
  - → Ease of manufacture and assembly
- Trials and feedback
- Re-design and manufacture

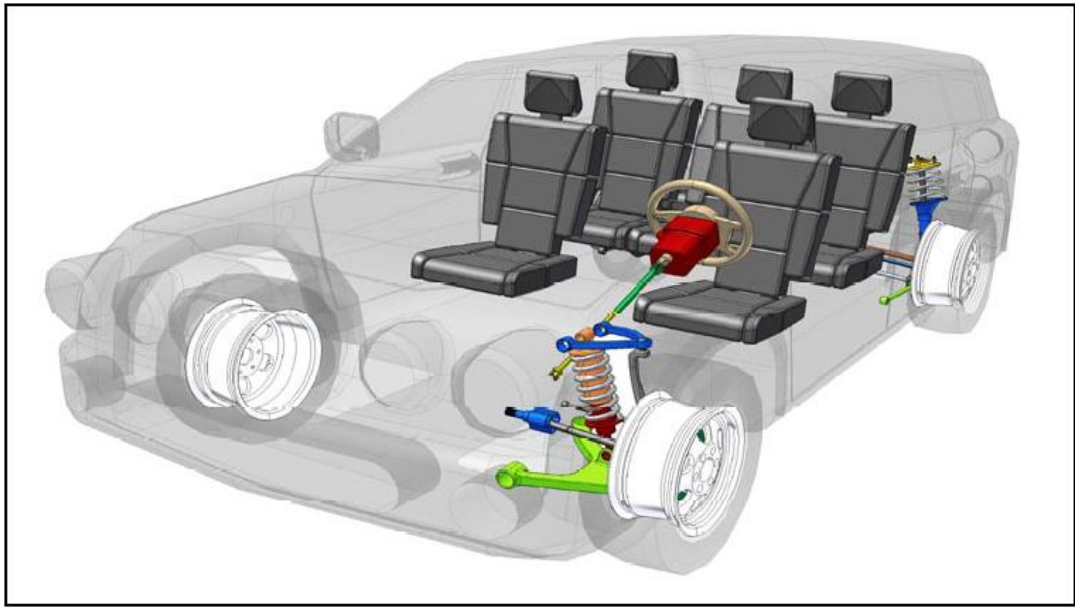
Case 3: Hyper-redundant manipulator

Multi-body systems & Degrees of Freedom

Industrial robot with six degrees of freedom



Automobile – several degrees of freedom



Source: ADAMS/Car

Wire, rope – deformable objects with infinite degrees of freedom

Proteins

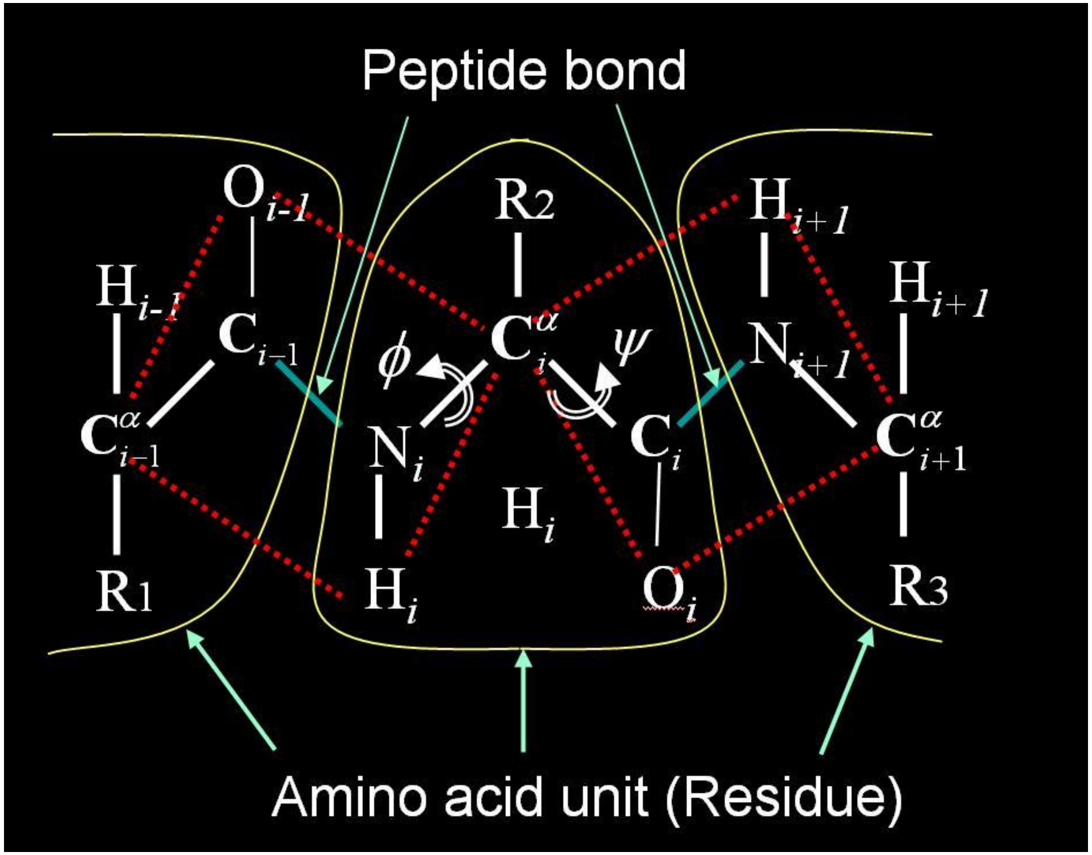
- Classical model – 20 amino acid residues in a serial chain with 50-500 residues – residues assumed to be rigid bodies

Two dihedral angles

Φ Ψ

- **Large number of degrees of freedom for any protein**

Folds to a specific shape under action of external forces between atoms and between solution and atoms



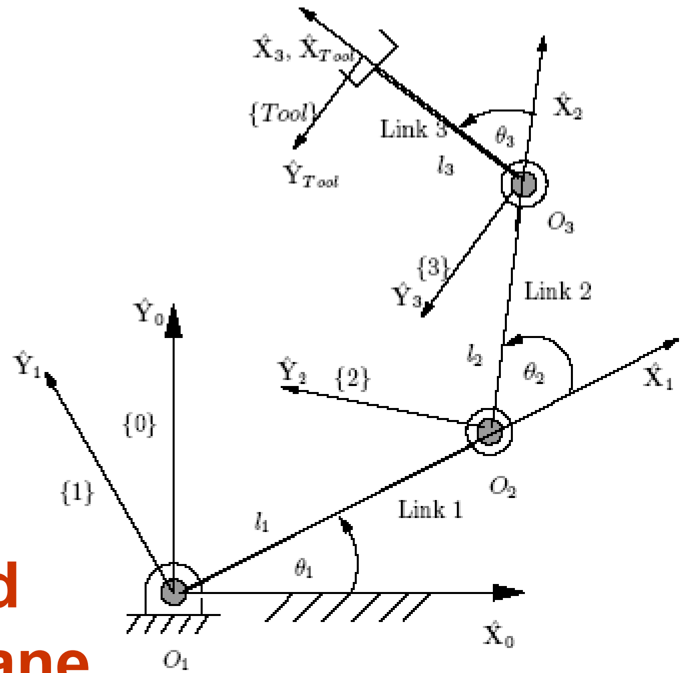
Redundancy

- A rigid body in 3D space has 6 degrees of freedom (*dof*)
- Two rigid bodies in 3D connected by a joint

  dof = 2 x 6 – No. of constraints imposed by joint

$$dof = \lambda(N - J - 1) + \sum_{i=1}^{J} F_i$$

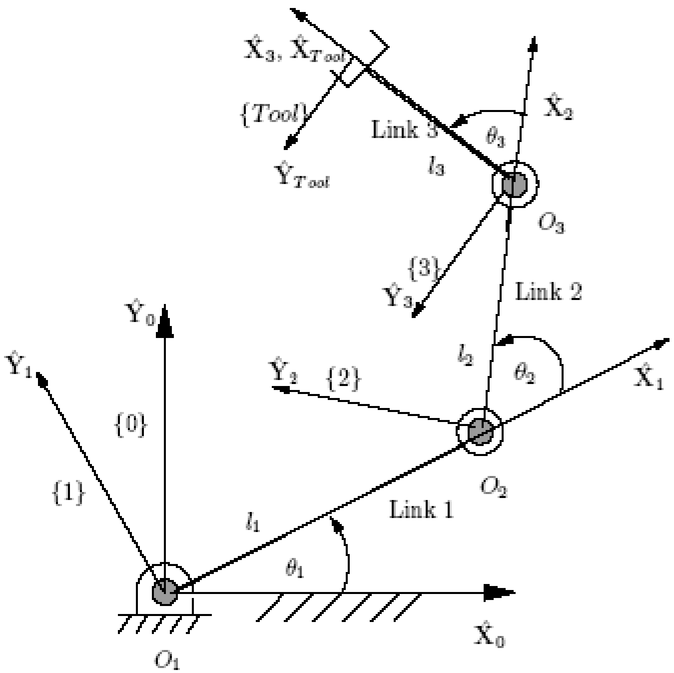
λ = 6 for spatial
= 3 for planar



***dof* = 3(4 - 3 - 1) + 3**
= 3

End-effector can be positioned and oriented *arbitrarily* in a plane

Redundancy (Contd.)



Planar 3R Manipulator

$$
\begin{aligned}
x &= l_1 c_1 + l_2 c_{12} + l_3 c_{123} \\
y &= l_1 s_1 + l_2 s_{12} + l_3 s_{123} \\
\phi &= \theta_1 + \theta_2 + \theta_3
\end{aligned}
$$

Given (x, y, ϕ) → Can obtain θ_1 θ_2 & θ_3

Non-redundant Case

Only (x, y) of interest

$$
\begin{aligned}
x &= l_1 c_1 + l_2 c_{12} + l_3 c_{123} \\
y &= l_1 s_1 + l_2 s_{12} + l_3 s_{123}
\end{aligned}
$$

Given (x, y) → Cannot obtain θ_1 θ_2 & θ_3

Redundant Case – infinitely many solutions possible

Resolution of Redundancy

Additional constraints imposed to solve for Θ for a given x

→ To enable unique solution for Θ

→ Known as **Resolution of Redundancy**

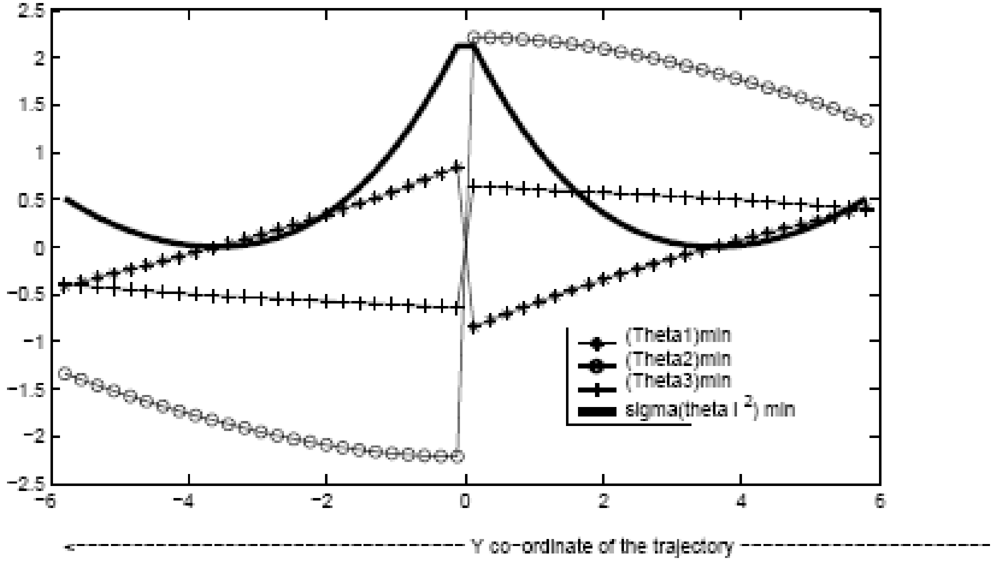
Optimization of an objective function

$$\text{Minimize } f(\boldsymbol{\theta}) = \theta_1^2 + \theta_2^2 + \theta_3^2$$

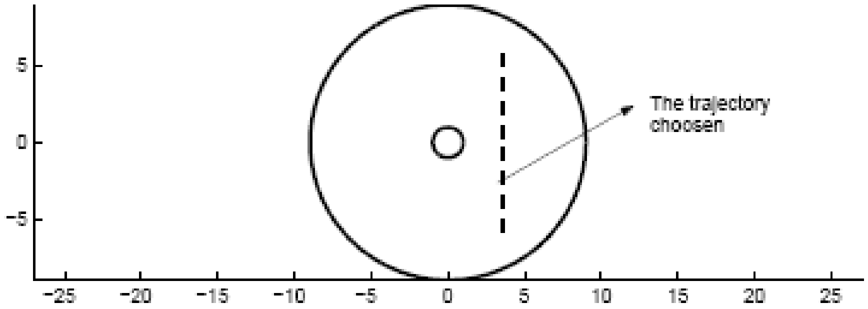
subject to

$$\begin{aligned} g_1(\boldsymbol{\theta}) &= -x + l_1 c_1 + l_2 c_{12} + l_3 c_{123} = 0 \\ g_2(\boldsymbol{\theta}) &= -y + l_1 s_1 + l_2 s_{12} + l_3 s_{123} = 0 \end{aligned}$$

Resolution of Redundancy



Plot of θ_1, θ_2 & θ_3



Resolution of redundancy
-- minimization of joint
rotations

Resolution of Redundancy

- **Other constraints imposed to solve for Θ for a given $\mathcal{X}$**

→ Avoiding obstacles during motion
→ Avoiding joint limits
→ Minimizing rotation at joints, joint rates, acceleration
→ Optimization of an objective function

- **Use of Pseudo-inverse**

$${}^{i}\mathcal{V} = [J(\Theta)]\,\dot{\Theta}$$

Derivative of the forward kinematics map

$$\dot{\Theta} = [J(\Theta)]^{\#}\,{}^{i}\mathcal{V} + ([U] - [J(\Theta)]^{\#}[J(\Theta)])\dot{\mathcal{W}}$$

$$[J(\Theta)]^{\#} = [J(\Theta)]^{T}([J(\Theta)][J(\Theta)]^{T})^{-1}$$

- **Minimizes** $\dot{\Theta}^{T}\dot{\Theta}$

Y. Nakamura 1991, *Advanced Robotics: Redundancy and Optimization*, Addison-Wesley

Resolution of Redundancy

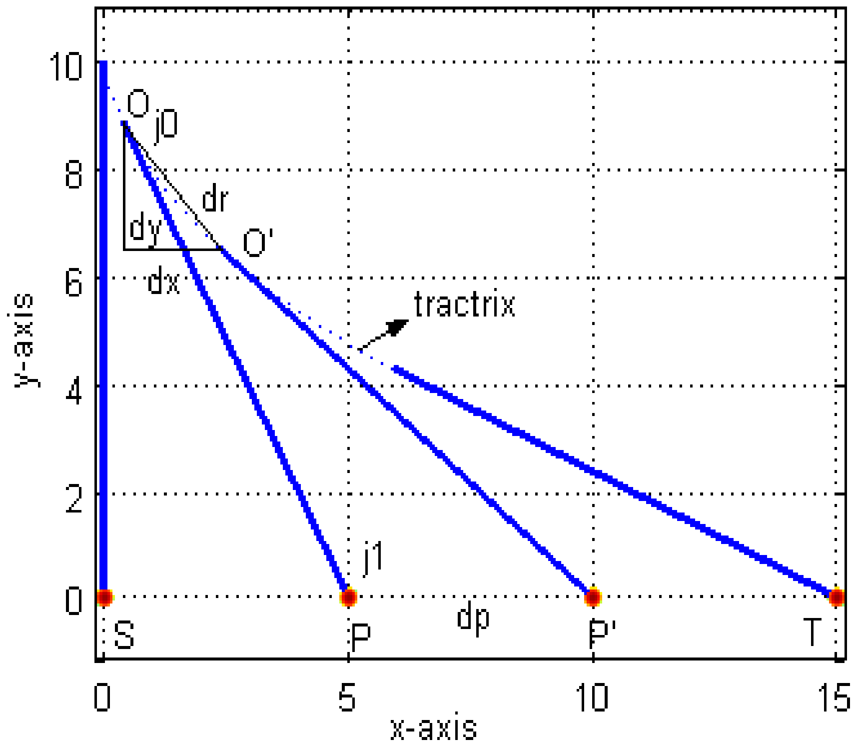
Task Space Approach

- Use of tractrix curve (hund or hound curve) Leibniz

http://mathworld.wolfram.com/Tractrix.html

- **A link moves such that the head P moves along the X axis and the *velocity* of tail *j0* is along the link.**

- **The curve traced by tail is a *tractrix***



Resolution of Redundancy

$$\frac{dy}{dx} = \frac{-y}{\sqrt{L^2 - y^2}}$$ ← Differential equation of a tractrix follows from velocity along link

Can be solved in closed-form

$$x = L \log \frac{y}{L - \sqrt{L^2 - y^2}} - \sqrt{L^2 - y^2}$$

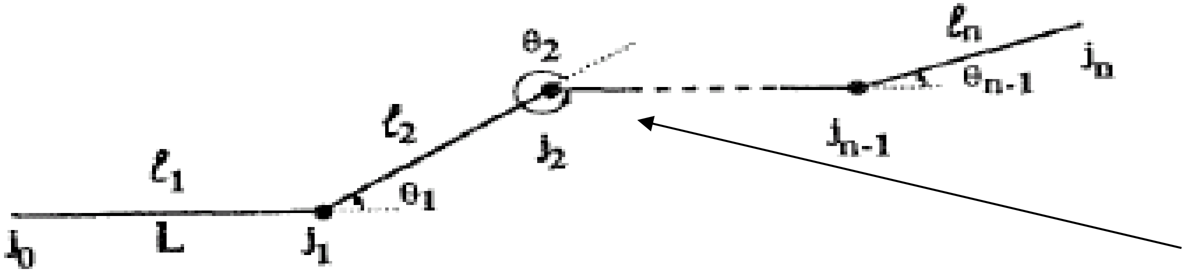
$$x(p) = p - L \tanh(\frac{p}{L}), \quad y(p) = L \operatorname{sech}(\frac{p}{L})$$ ← In parametric form

- Some properties of tractrix

→ For an infinitesimal motion of head (*dp*), the length of path traversed by tail (*dr) is minimum of all possible paths of tail*

→ $dr \leq dp$ *equal if velocity of head is along link*

Tractrix Applied to Redundant System



Redundant system or discretised flexible system

- $\delta_n, \delta_{n-1}, \ldots$ - displacements of joints $j_n, j_{n-1}, \ldots$

Lemma 1

$$\delta_0 \le \delta_1 \le \ldots \le \delta_{n-1} \le \delta_n$$

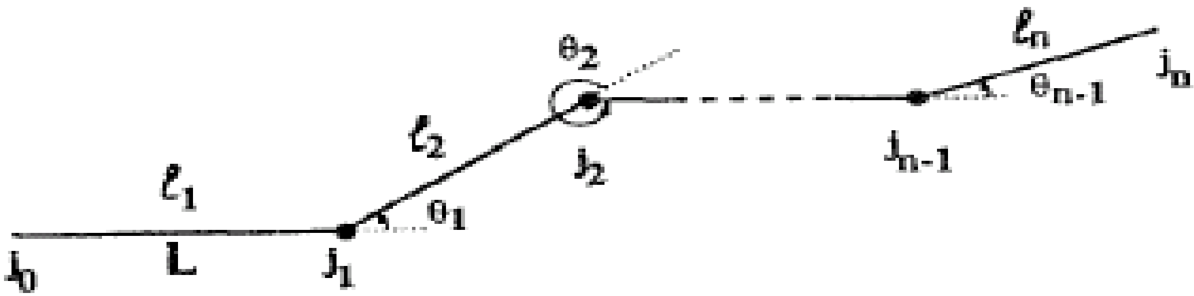
Lemma 2

$$\sum_{i=0}^{i=n-1} \delta_i = \min$$

The effect of the motion of a end is “washed out” as we traverse down the chain

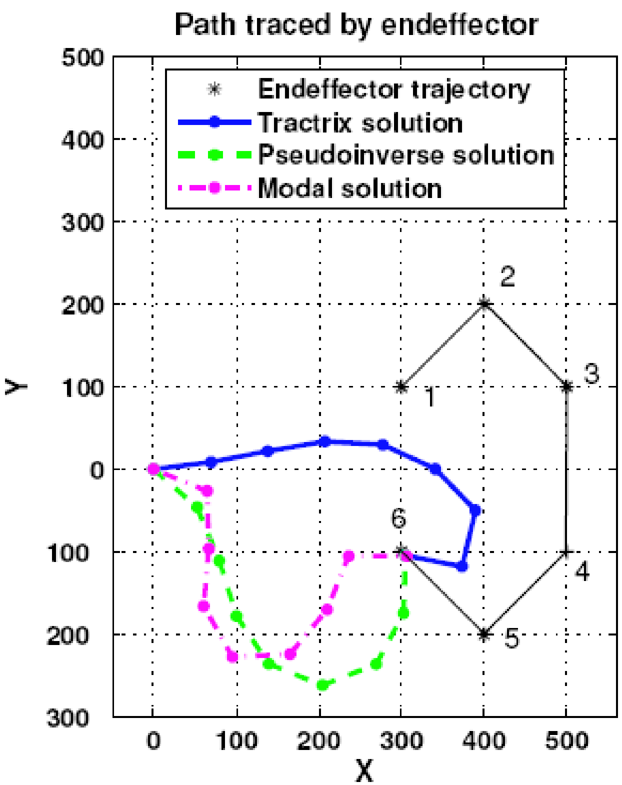
Reznick & Lumelsky, Advanced Robotics, 1995

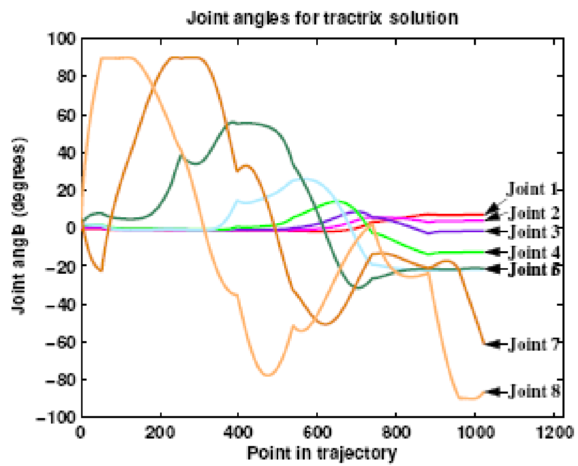
Algorithm for tractrix based resolution of redundancy



- Serial multi-body system as rigid links connected by joints – R joint in plane, U (or S) joint in 3D
- Discretise given motion of end (or any point) as “small steps” in 3D
- Find location of tail using closed-form tractrix solution
- New location of tail = desired motion of head of previous or subsequent link
- Recursively go to ends of chain

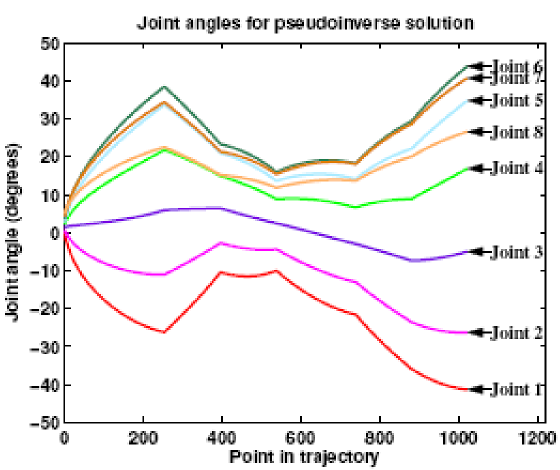
Numerical Simulation Results
Piece-wise straight lines

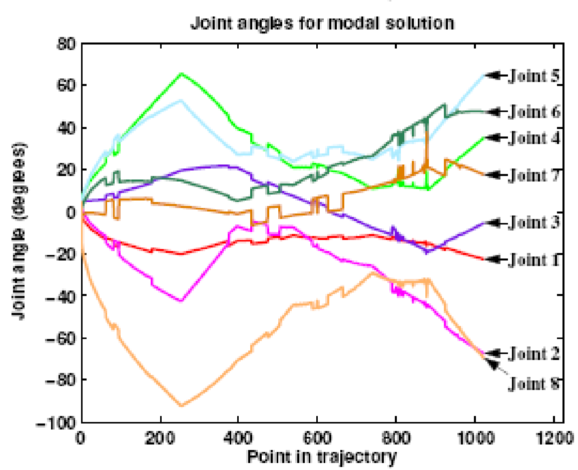




8 – link planar Hyper-redundant Manipulator

Each link 70 mm long

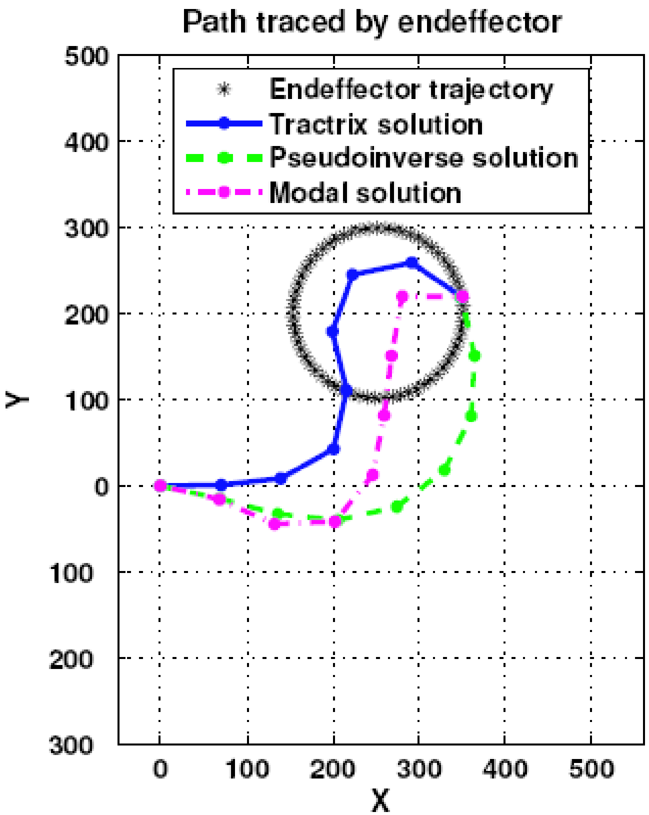


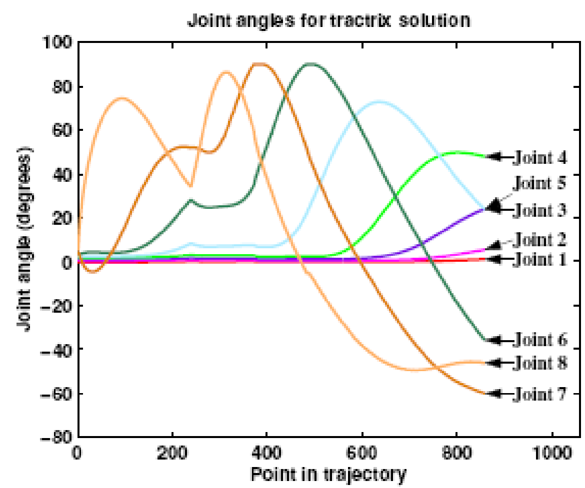


Plot of 8 joint variables Computed using
1) Tractrix
2) Pseudo-inverse
3) Modal approach

Sreenivasan et al., MMT 2010

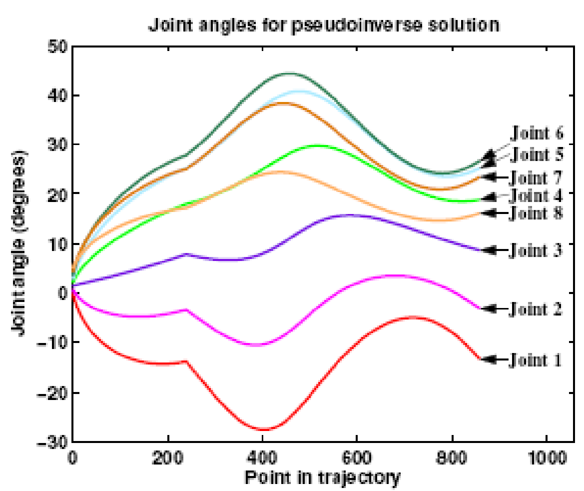
Numerical Simulation Results
Circular trajectory

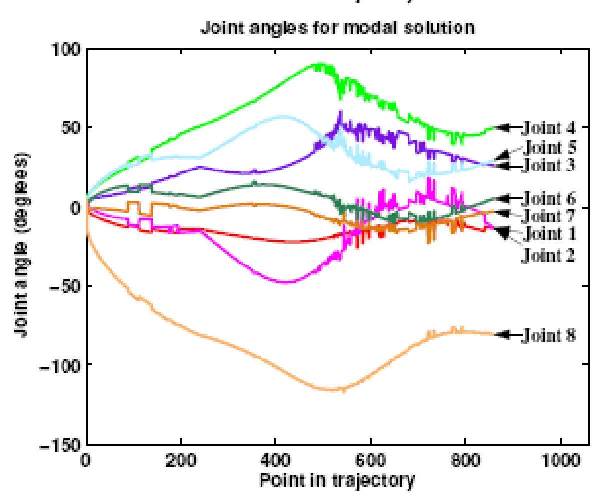




8 – link planar
Hyper-redundant
Manipulator

Each link 70 mm
long



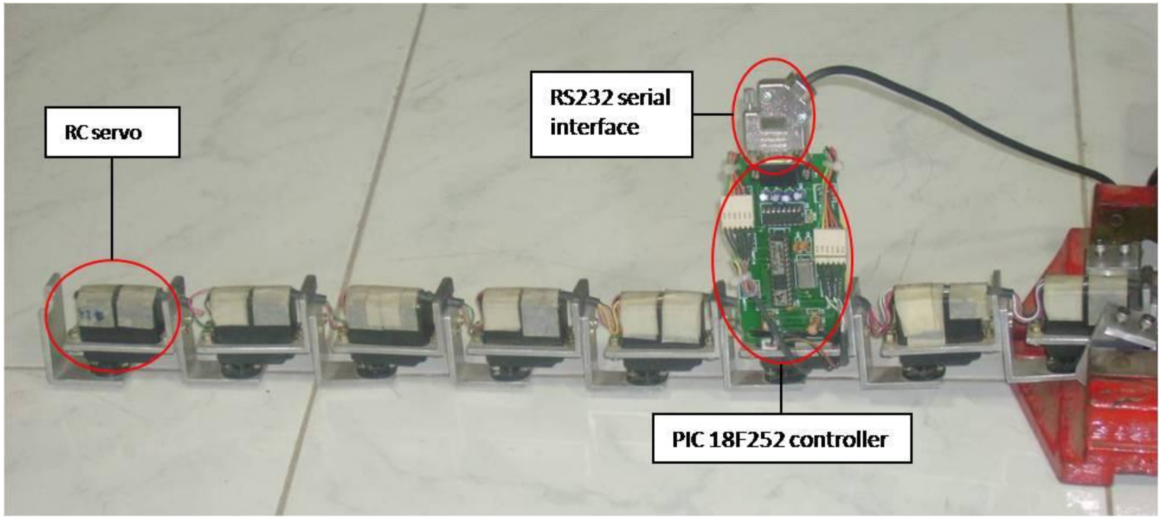


Plot of 8 joint variables
Computed using

1) Tractrix
2) Pseudo-inverse
3) Modal approach

Sreenivasan et al., MMT 2010

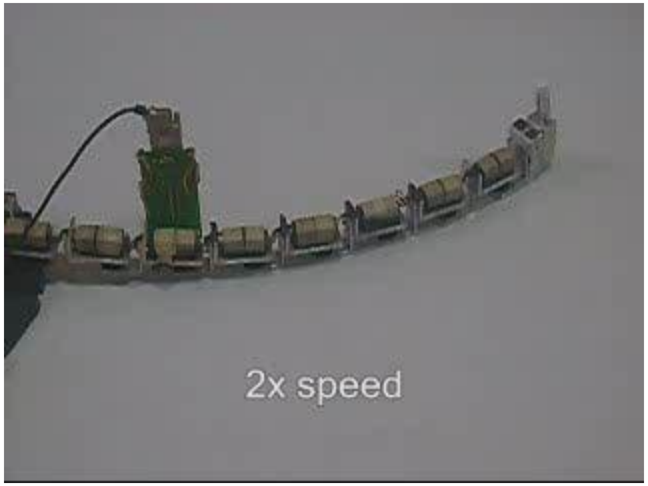
Experimental set-up



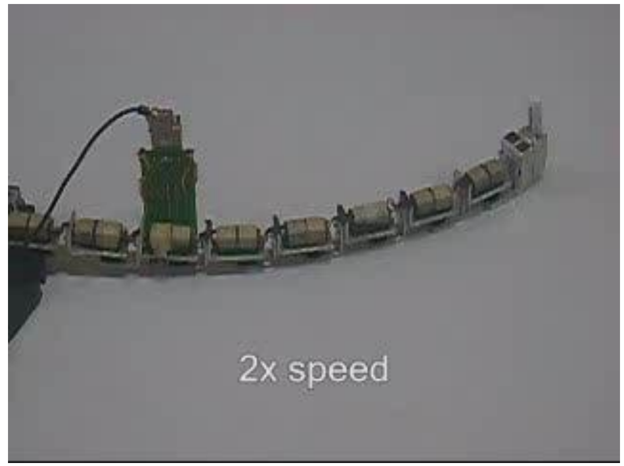
- 8-link serial chain
- RC servo actuators - ±90^o
- Custom PIC18F252 controller board
- Serial interface to PC for joint angle commands
- Low tracking accuracy and no dynamics compensation
  - Low speed operation
  - Trajectories chosen to avoid self-intersection and to maintain joint angle limits

Ravi et al., *ASME JMR, 2010*

Videos of Straight-line Trajectories

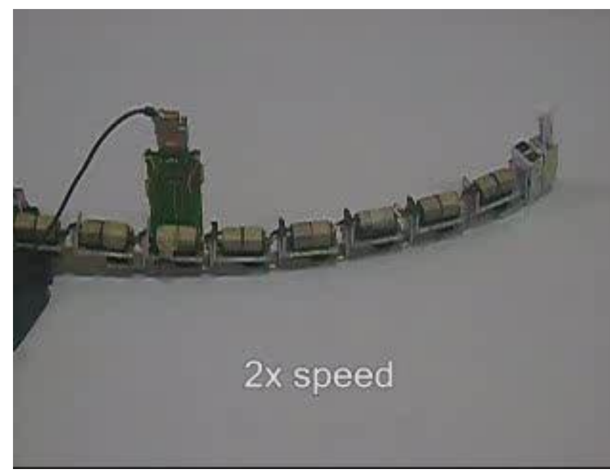


Modal approach



Pseudo-inverse

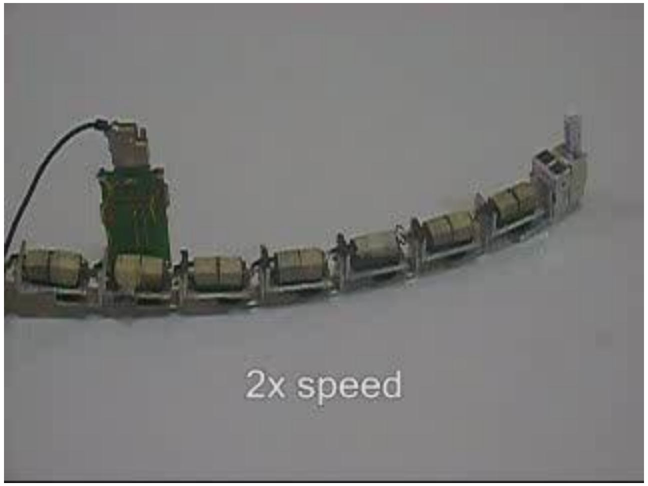
Smoothest Motion →



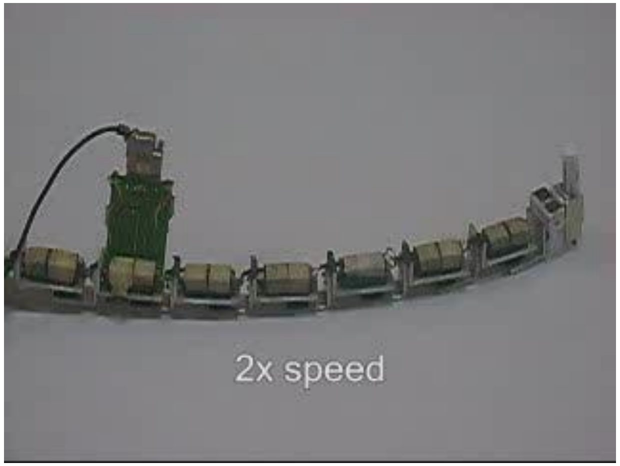
Tractrix based approach

Ravi et al., *ASME JMR, 2010*

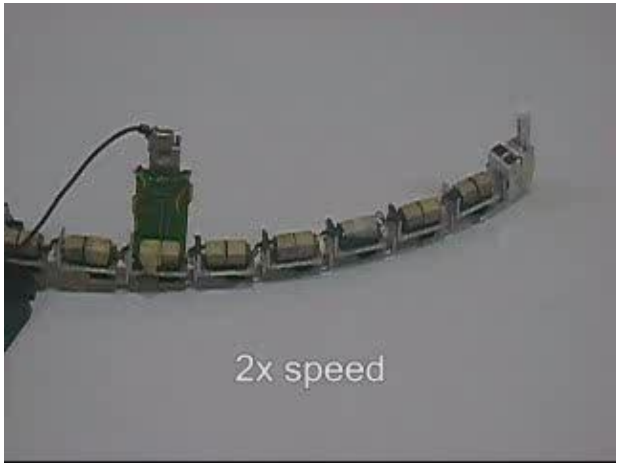
Videos of Circular Trajectory



Modal approach



Pseudo-inverse



Tractrix based approach

Smoothest Motion →

Ravi et al., *ASME JMR, 2010*

Free Hyper-redundant Manipulator

8 link hyper-redundant manipulator

→Base is free to move on smooth tiled floor

→Head given a series of desired (*x*,*y*) locations

→Joint rotations computed according to tractrix approach

Power and desired joint rotation values computed on PC and sent via cable

V C Ravi @CAIR

Other Applications

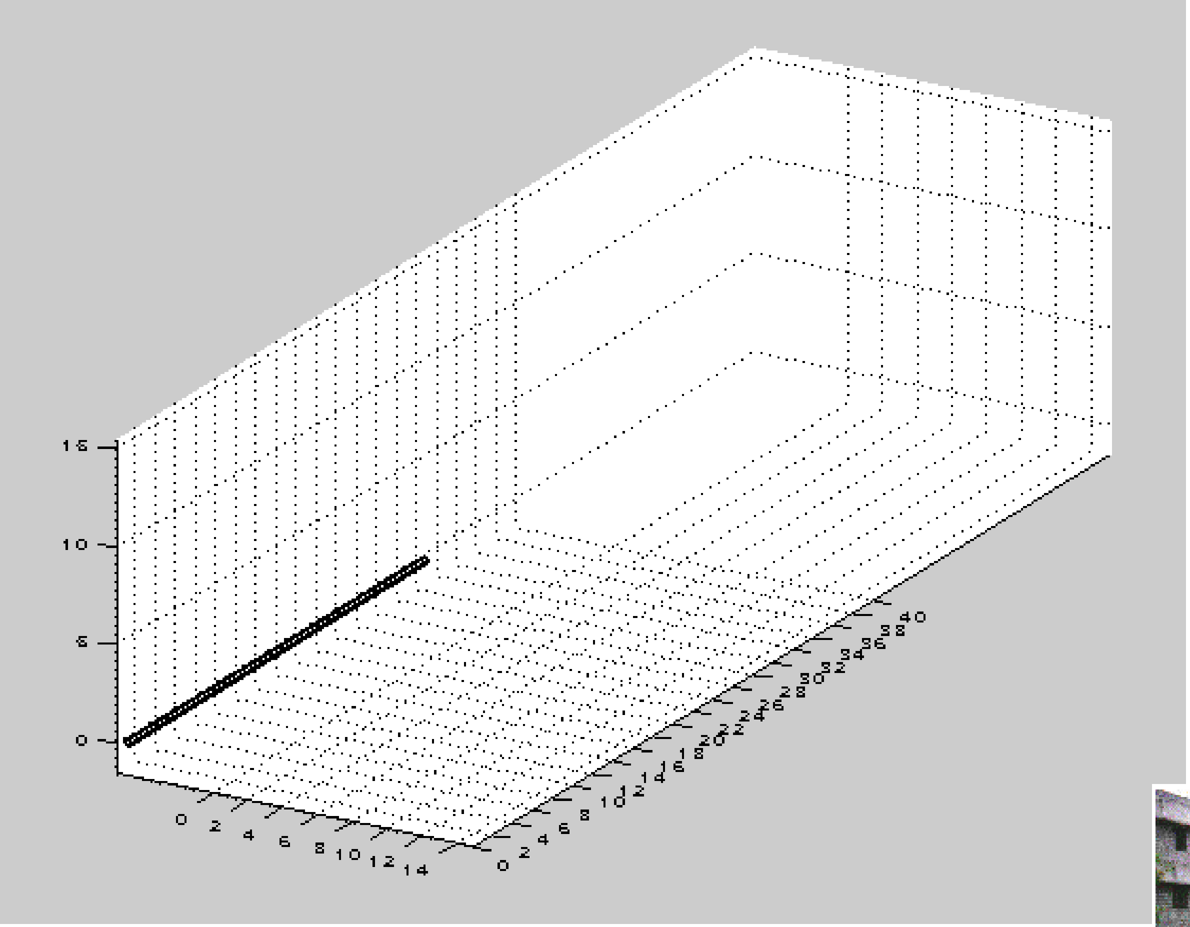
Tractrix based approach

→ Is of linear complexity

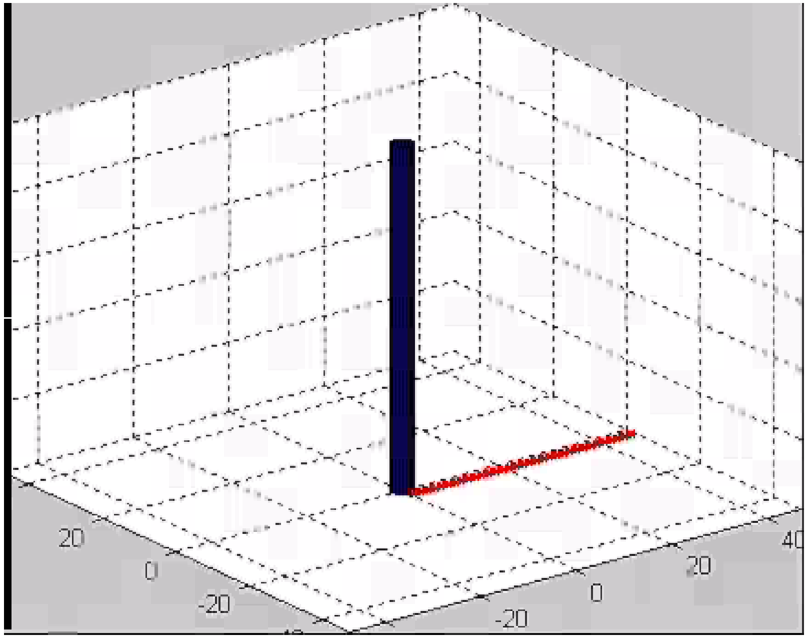
→ Appear more natural as motion is washed out

- Winding a wire around a mandrel – spring
- Motion of a rope
- Motion of the body of a snake with chosen head motion
- Simulating tying of a knot with one hand
- Tying of a knot with two hands

Example - Motion of Rope

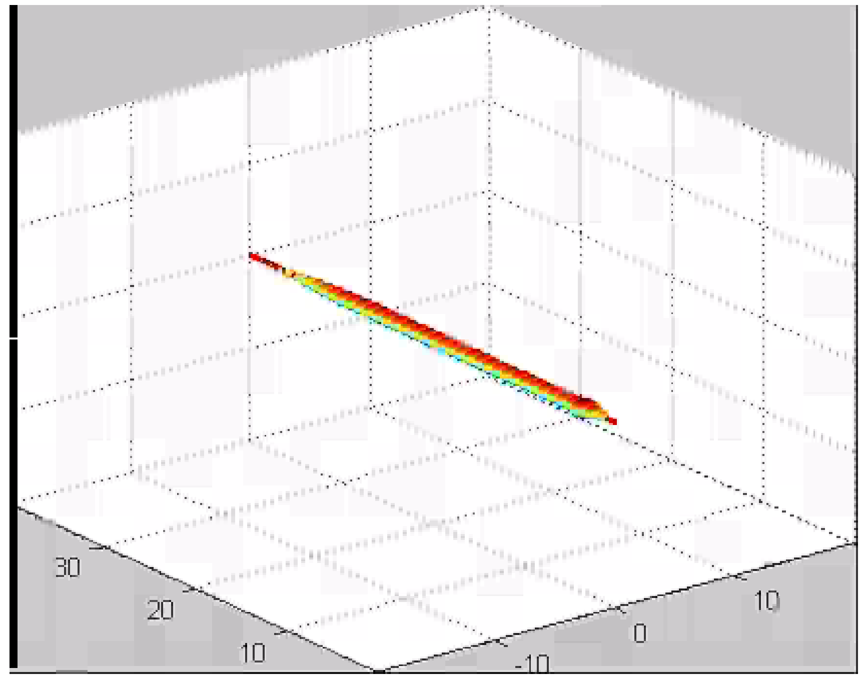


Examples



Winding a wire on a rod

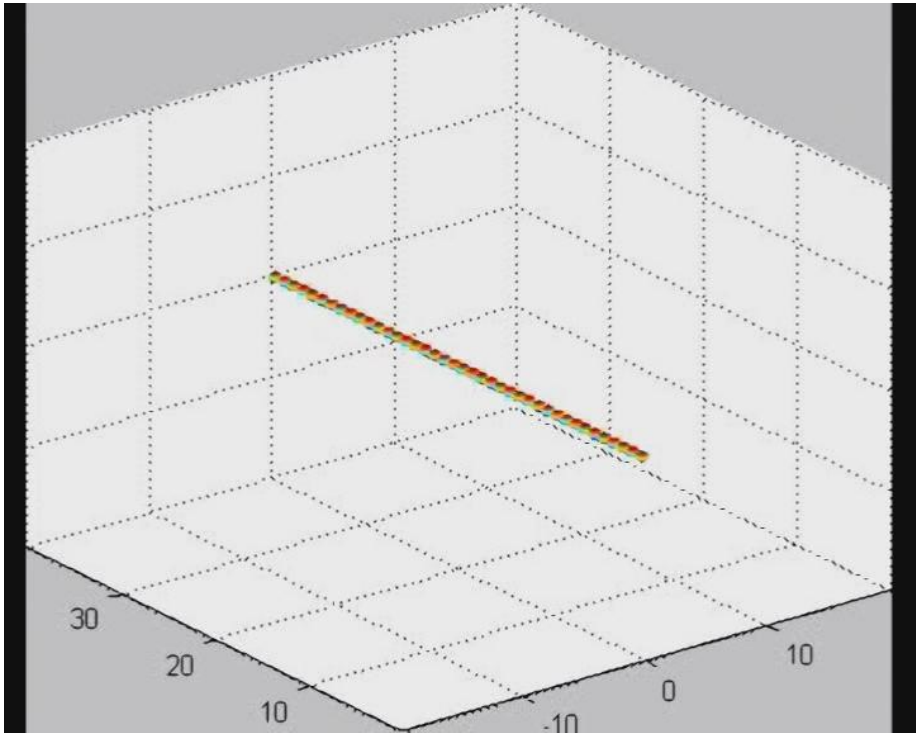
Simulated motion of a snake in 3D

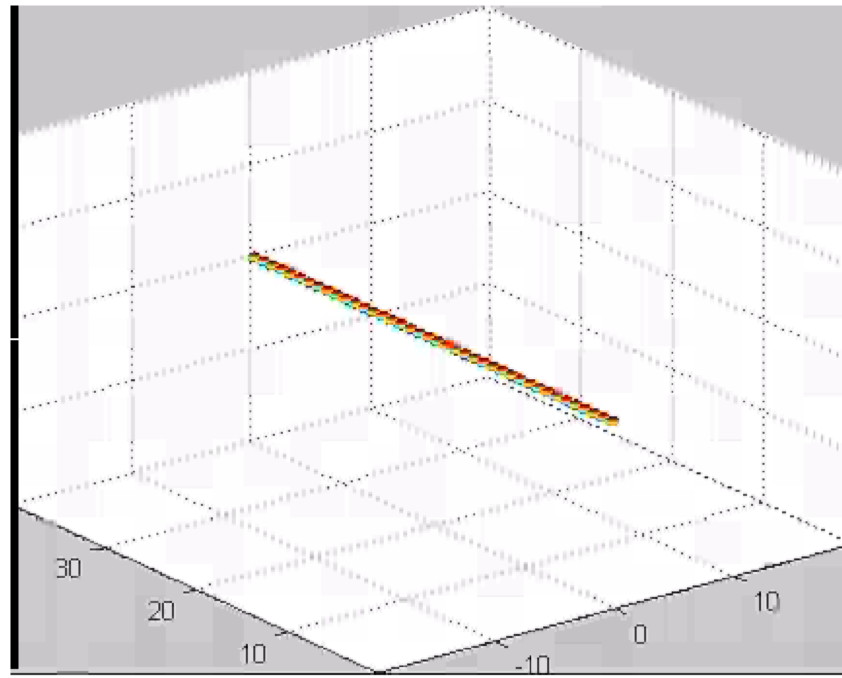


40 rigid links of 1 unit long. Links connected by spherical joints

Sreenivasan et al., MMT 2010

Example – tying knot in a rope





- 40 links, only one end is moved

- 40 links, both ends moved

Sreenivasan et al., MMT 2010

Summary of Case 3

- A new approach to resolution of redundancy & comparison with existing methods
- Equations developed for a purely kinematic based approach applicable for planar and spatial motions
- Closed-form and efficient – linear complexity
- Appear to be more natural – disturbances die out
- Validated by a prototype 8 link redundant robot

Conclusions

Kinematic Analysis and Simulations

Design

Prototyping, Testing and Validation

Redesign

3 Case Studies → Equations to Embodiment

THANK YOU

More Information – http://www.mecheng.iisc.ernet.in/~asitava