# A Skew-Axis Design for a 4-Joint Revolute Wrist

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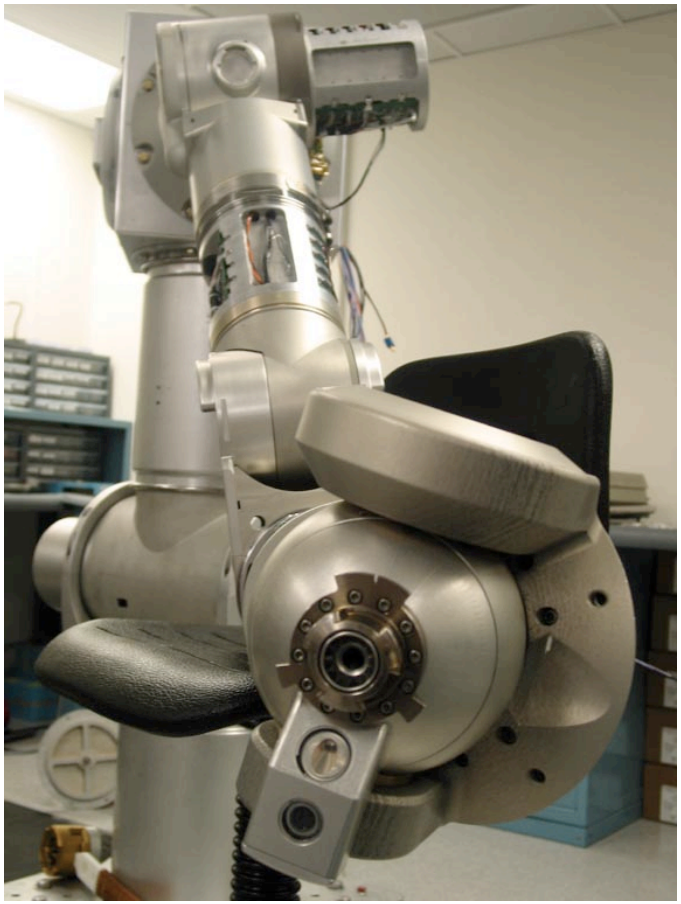
# Outline

- Objectives
- 4-Axis Wrist Design
- Joint/Tool Workspace
- Singularities
- Inverse Kinematics
- Simulation Results
- Experiments
- Conclusions



# Objectives

- **Introduce an alternative 4-axis wrist with larger tool workspace**
- **Map the wrist rotational workspace and singularities**
- **Present inverse kinematics options for controlling the wrist**
- **Simulation/hardware results for wrist operation**



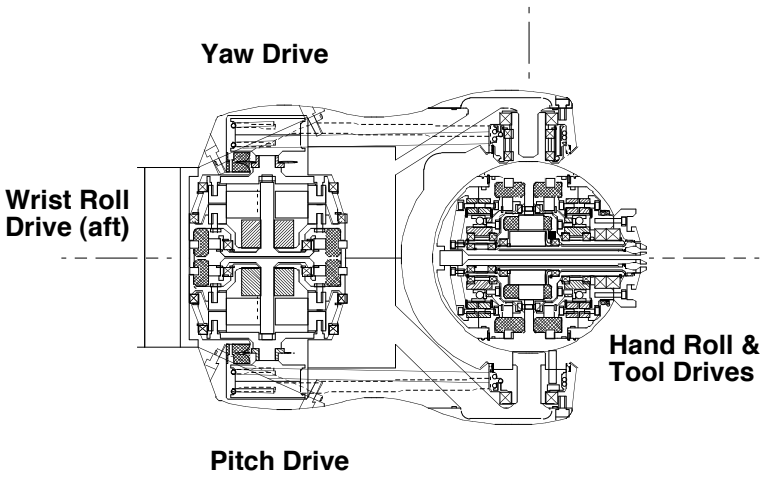
# Why a 4-Axis Wrist?

- **Advantages**
  - **Singularity-free access to rotational workspace**
  - **Avoid joint limits through "self-motion"**
  - **Lower joint velocities than 3-axis designs**
- **Disadvantages**
  - **Additional hardware required**
  - **Greater computational complexity**
  - **More singularities in the workspace**

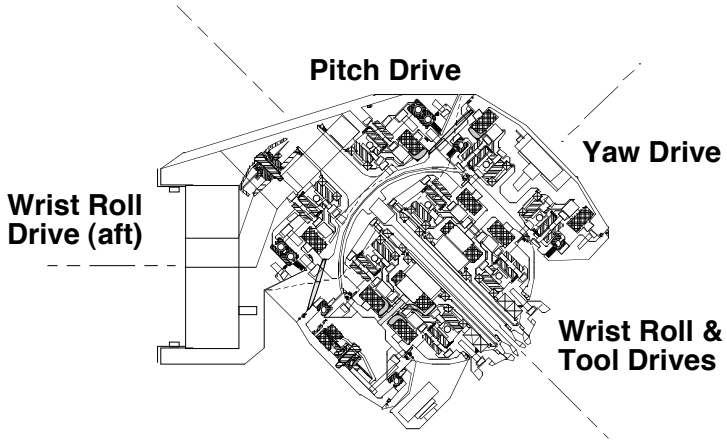
# Why a Skew Axis?

- **Lower interference of the tool with the forearm extends pitch travel**
- **Single-sided support of the inner wrist allows for greater yaw range**
- **Frontal area of the wrist reduced by skew layback of pitch actuator**

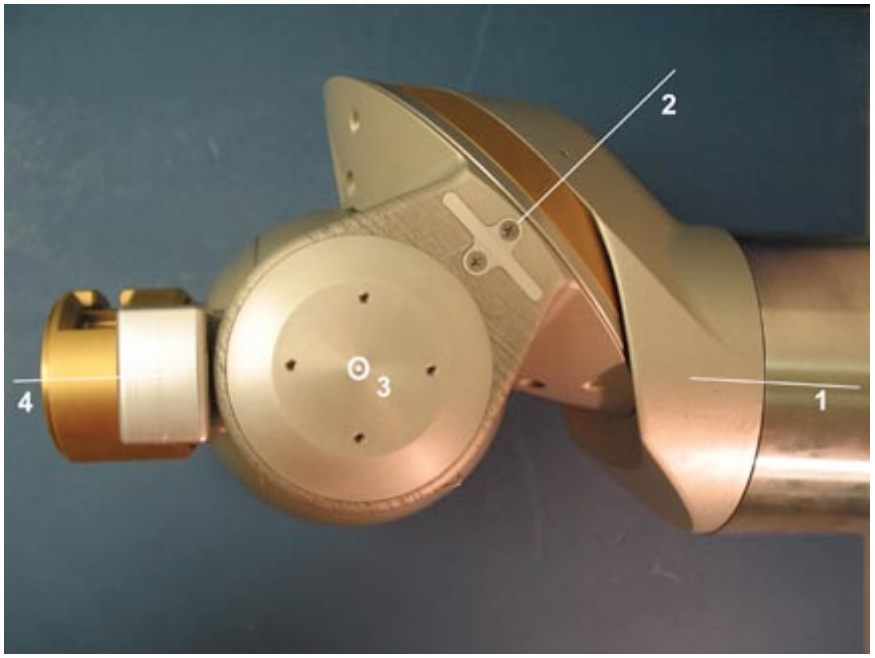
Orthogonal 4-axis

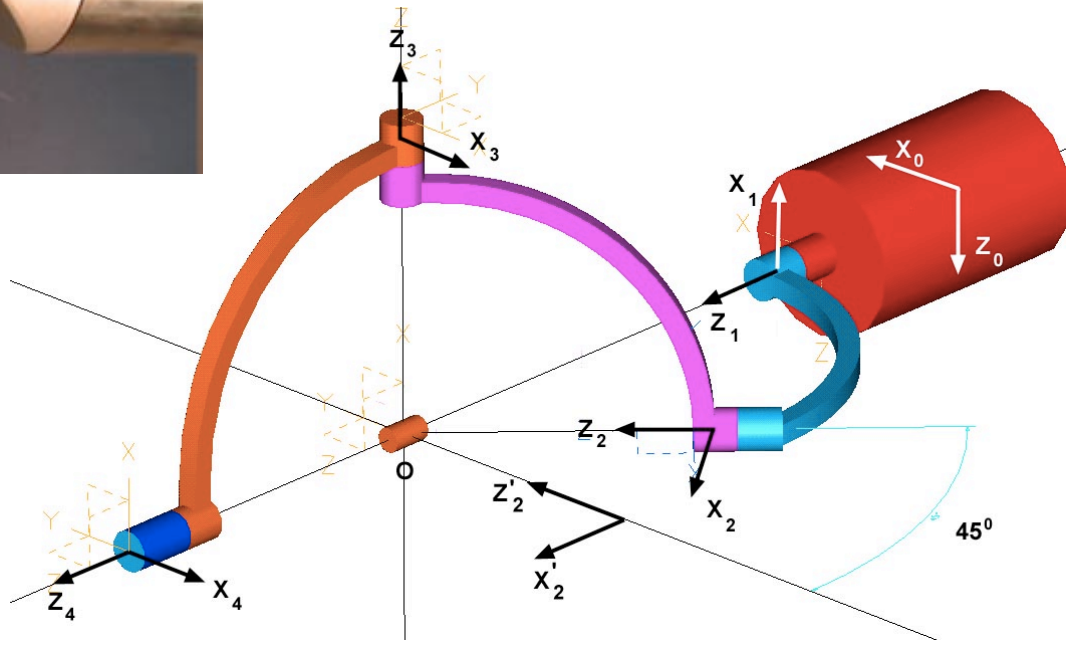



Skew 4-axis



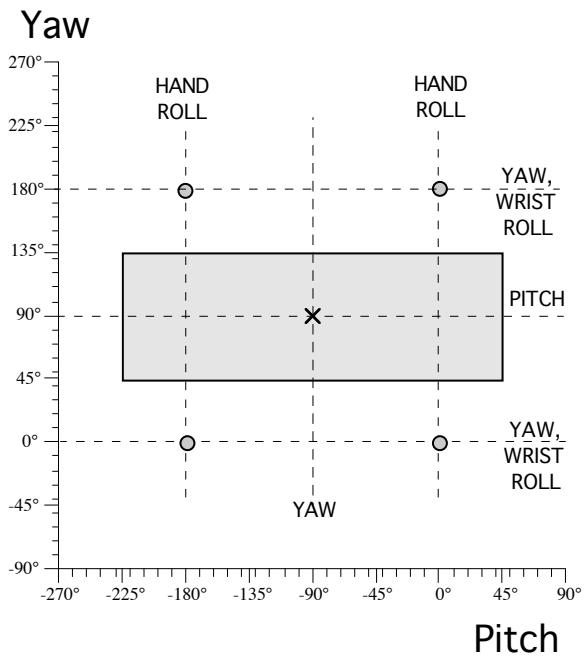
# 4-Axis Skew Wrist Design



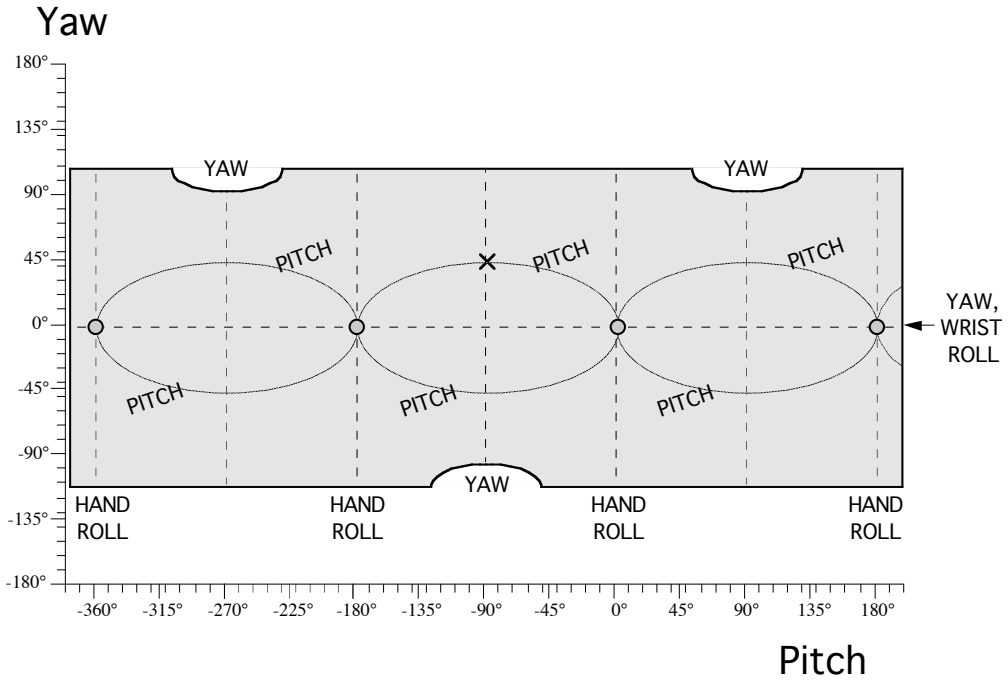



# Jointspace Comparison

## 4-AXIS ORTHOGONAL



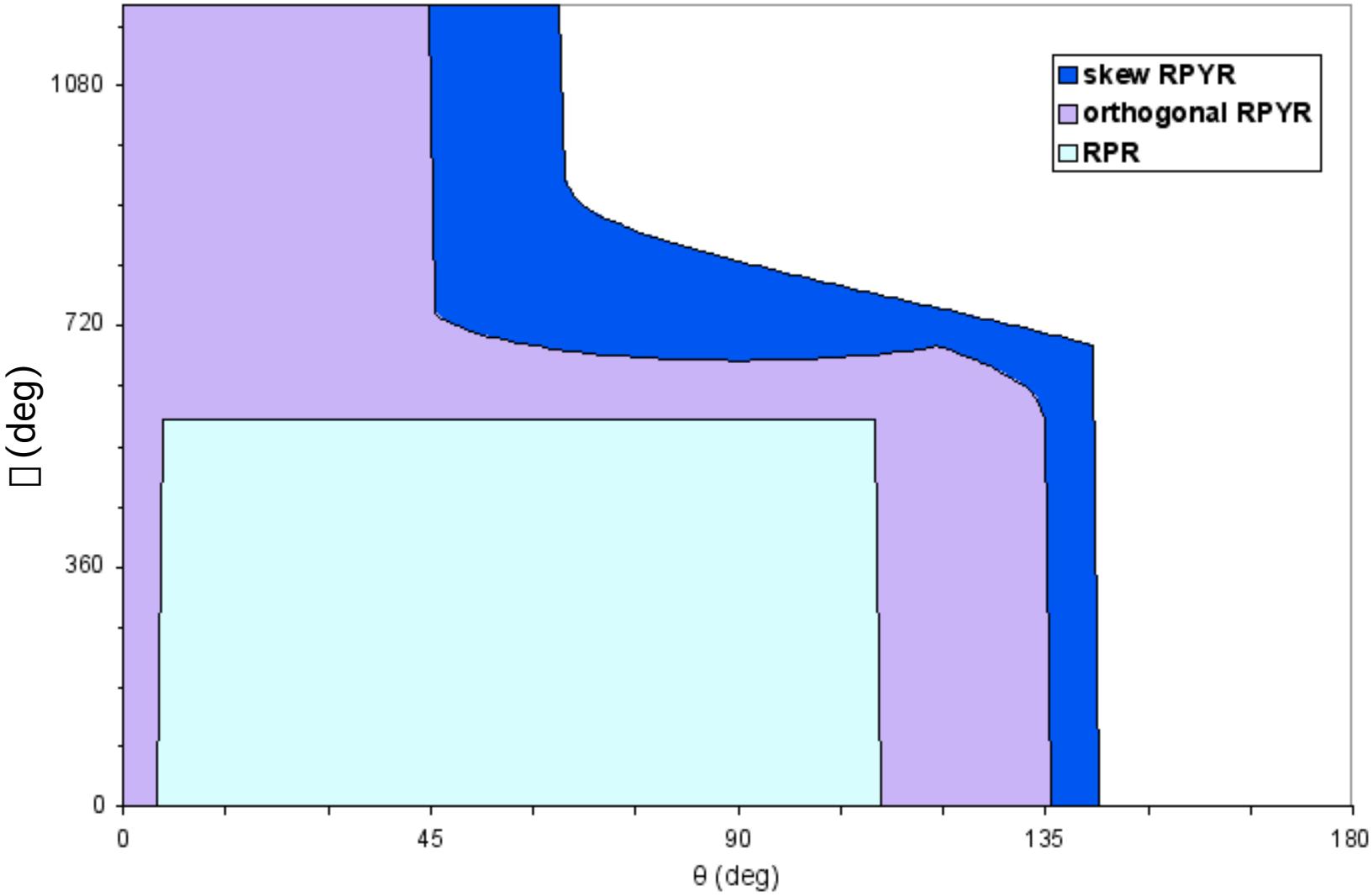

## 4-AXIS SKEW




-- Type I singularity (3DOF)

Type II singularity (2DOF)

# Toolspace Comparison



# Workspace Singularities

## Type I – 3 Axes Become Coplanar

| Coplanar Axes | Condition |
|---|---|
| 1, 2, 3 | $\theta_2 = 0°, \pm 180°$ |
| 1, 2, 4 | $\theta_2 = \pm 90°$ or $\theta_3 = 0°$ |
| 1, 3, 4 | $\tan(\theta_3) = -\sin(\theta_2)$ |
| 2, 3, 4 | $\theta_3 = 0°, \pm 180°$ |

## Type II – 4 Axes Become Coplanar

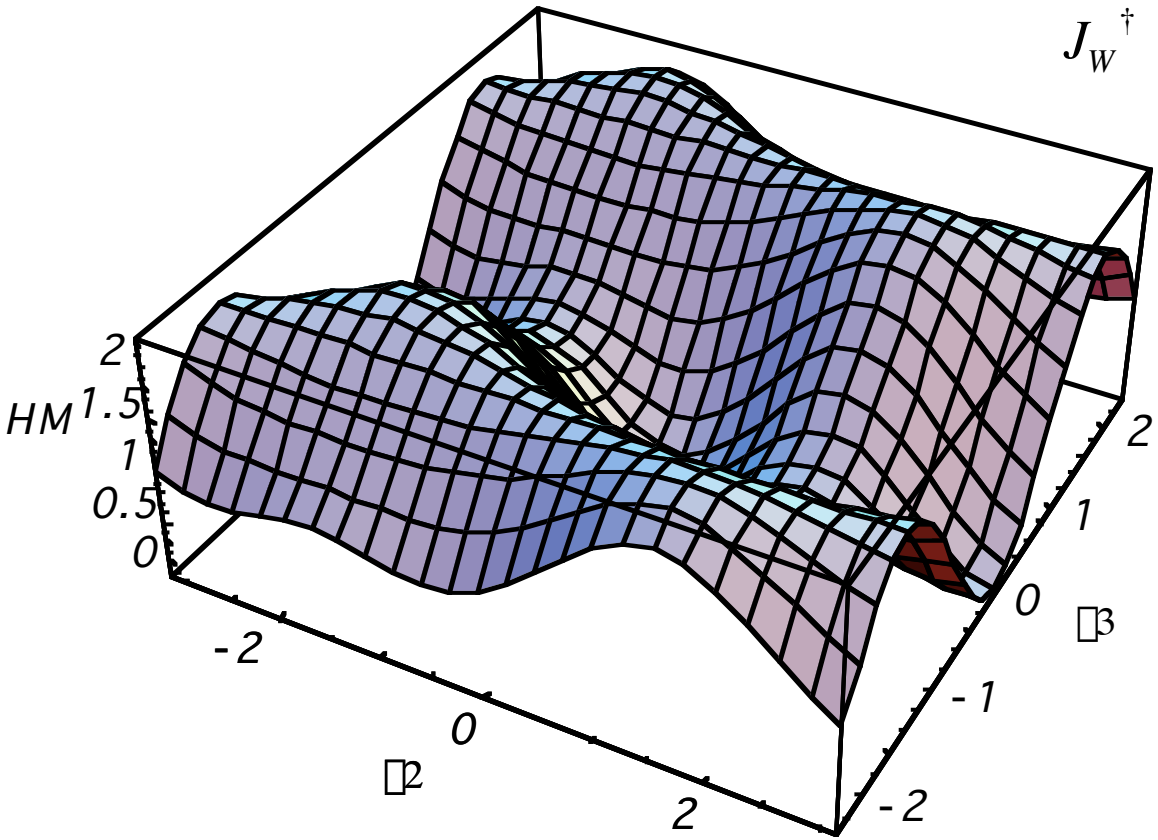
$\theta_2 = 0°, \pm 180°$
& $\theta_3 = 0°, \pm 180°$

# Manipulability Index

$$H_M = \sqrt{\left| J_w J_w^{\,T} \right|}$$

Pseudoinverse:

$$J_W^{\,\dagger} = J_W^{\,T} \left( J_W J_W^{\,T} \right)^{-1}$$



# Inverse Kinematics Approaches

## Generalized Inverse

Full 4-axis control with self-motion for singularity and joint limit avoidance

Joystick Command

$$\dot{\theta}_W = J_W^{\dagger}\dot{r} + (I - J_W^{\dagger}J_W)r_{\varnothing}$$

$$r_{\varnothing} = \left[k_M \nabla H_M + k_J \nabla H_J\right] t$$

Manipulability Gradient

Joint Limit Gradient

## Extended Jacobian

3-axis control to get Rotational command, Independent hand roll

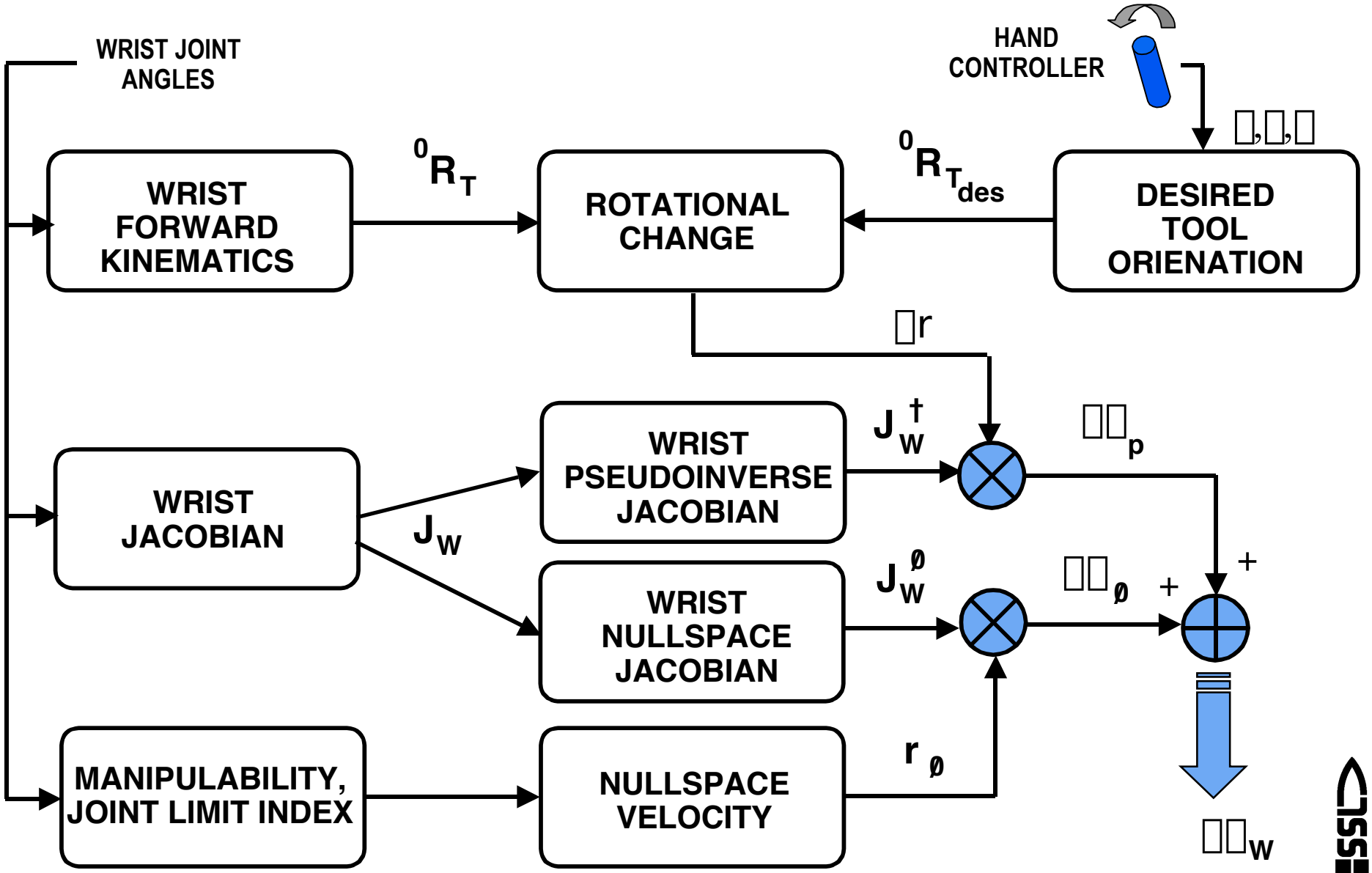
Joystick Command

$$\dot{\theta}_{1-3} = J_{123}^{-1}\dot{r}$$

$$\dot{\theta}_4 = \dot{\theta}_{HR}$$

Hand Roll Command

# Generalized Inverse Kinematics



# Inverse Kinematics Tradeoffs

- **Generalized Inverse**
  - **+ Automatic singularity and joint limit avoidance**
  - **+ Locally minimum joint velocities**
  - **+ Only 3-axis rotational input required**
  - **- Self-motion can be disrupting to operator**
- **Extended Jacobian**
  - **+ Cyclic motion**
  - **+ Direct control of yoke axis camera**
  - **+ Direct control of hand roll (tool axis)**
  - **- Manual singularity avoidance**
  - **- Greater motion of joints is more likely to cause joint limiting**

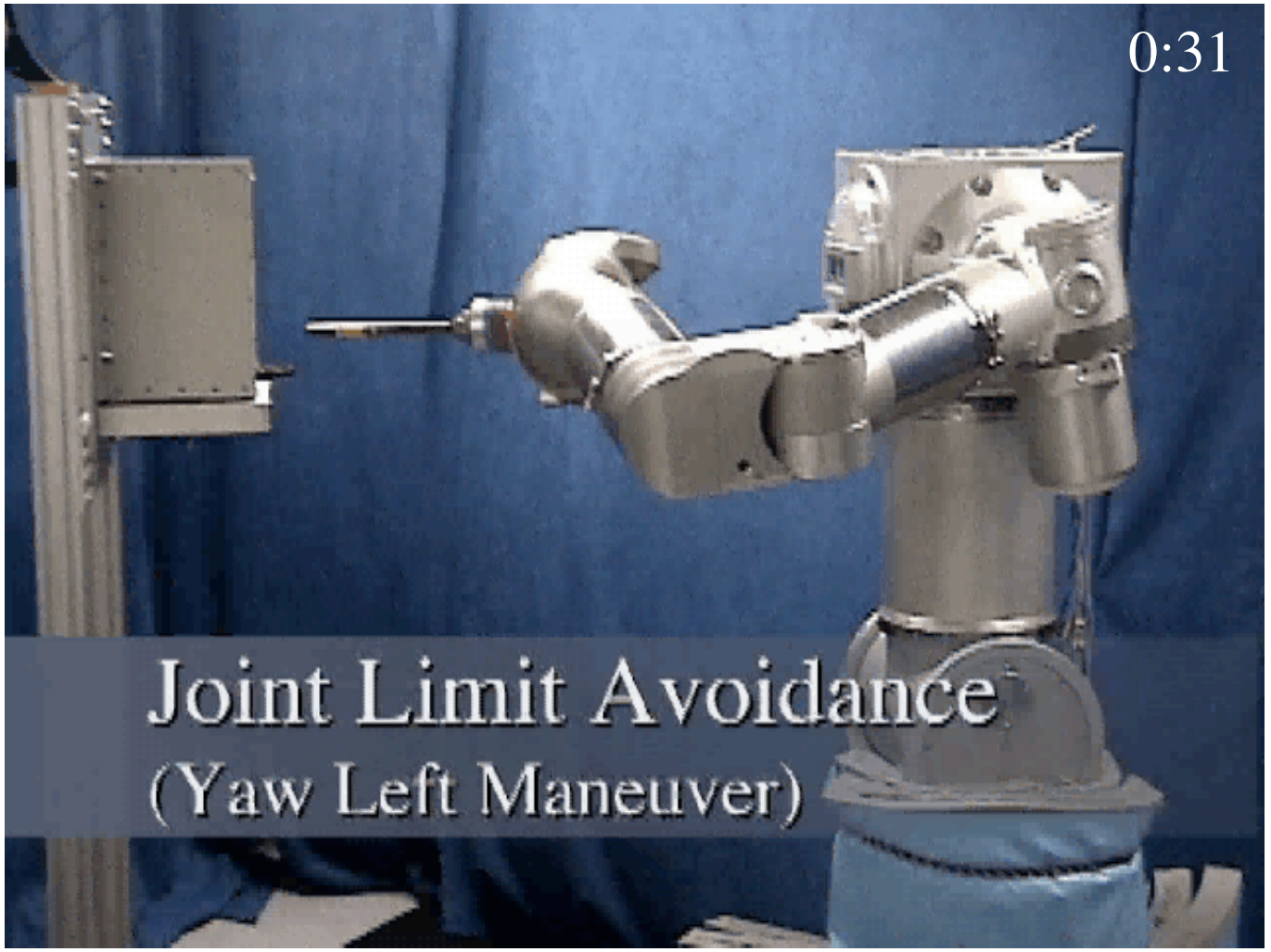


# Wrist Run-In Testing

# Inverse Kinematics Modes


4-DOF w/self-motion
3-DOF/Hand Roll Control

# Joint Limit Avoidance

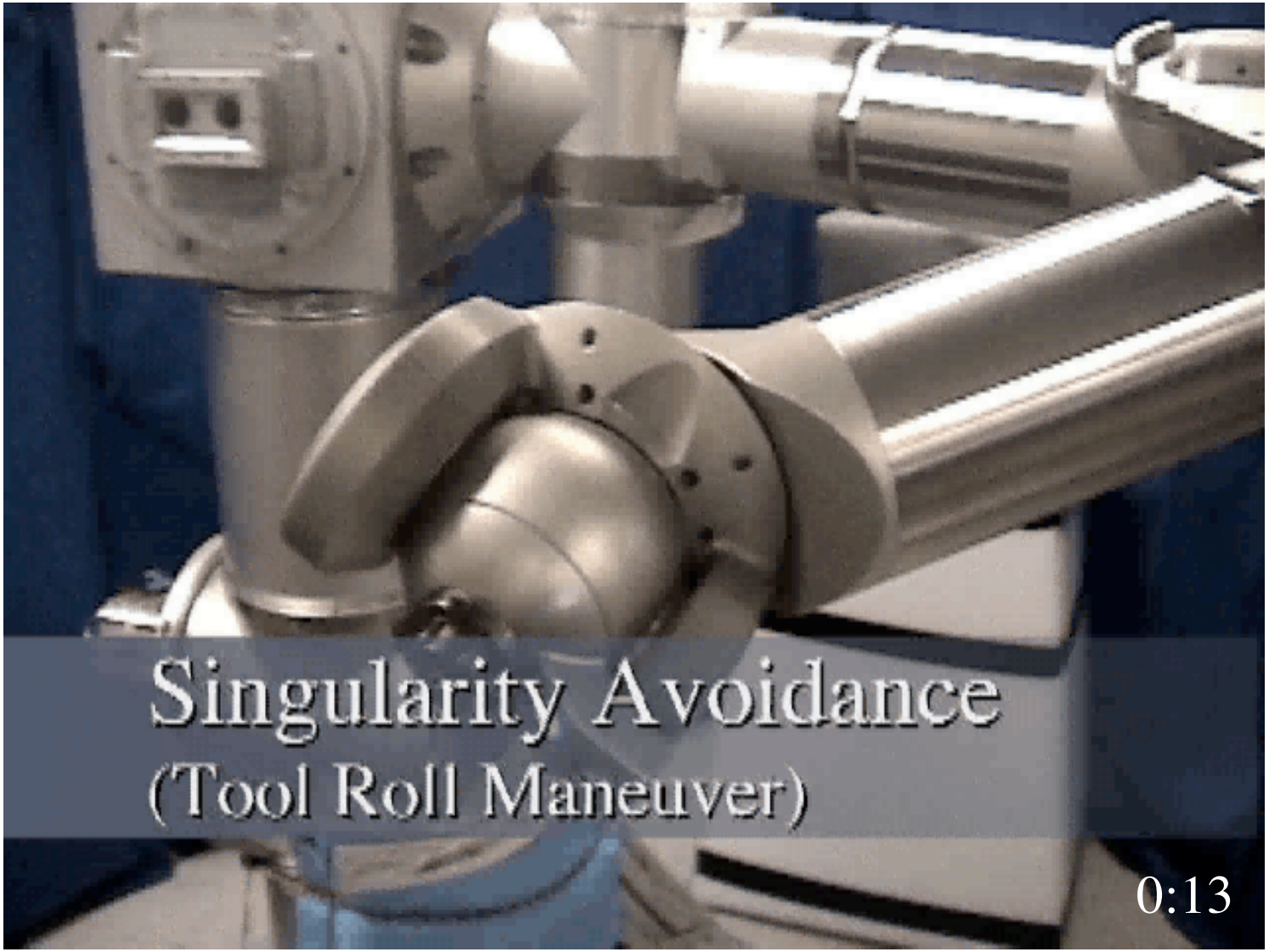



CCW yaw limit during 3-DOF control;
wrist transitions to 4-DOF control

# Singularity Avoidance (Simulation)


Tool Roll Simulation:
- Pseudoinverse
- Pseudoinverse with self-motion

# Singularity Avoidance (Experiment)




Forearm rolls to avoid singularity

# Conclusions

- **Skewing the pitch axis significantly increases the pitch and yaw range over the orthogonal design**
- **The singularity regions for the skew design are significantly more complex**
- **The generalized inverse method is most useful for large range of motion when singularities and joint limits are more likely to be encountered**
- **The extended Jacobian approach is more effective during close-proximity tasks when controlling the wrist camera and hand roll directly is critical**

# Acknowledgements

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**The Ranger Team**