The 14th International Conference on Flexible Automation and Intelligent Manufacturing (FAIM2004)

Powered Exoskeleton for Industrial Applications

Gary M. Bone, Po Wah Chan and Matthew Lahey

Robotics and Manufacturing Automation Laboratory,

McMaster Manufacturing Research Institute (MMRI).

Introduction

- When compared with humans, robots have superior strength and endurance, and vastly inferior intelligence.
- A powered exoskeleton (PEX) is a robotic device that is attached to a person's body and is controlled by them.

Introduction (page 2)

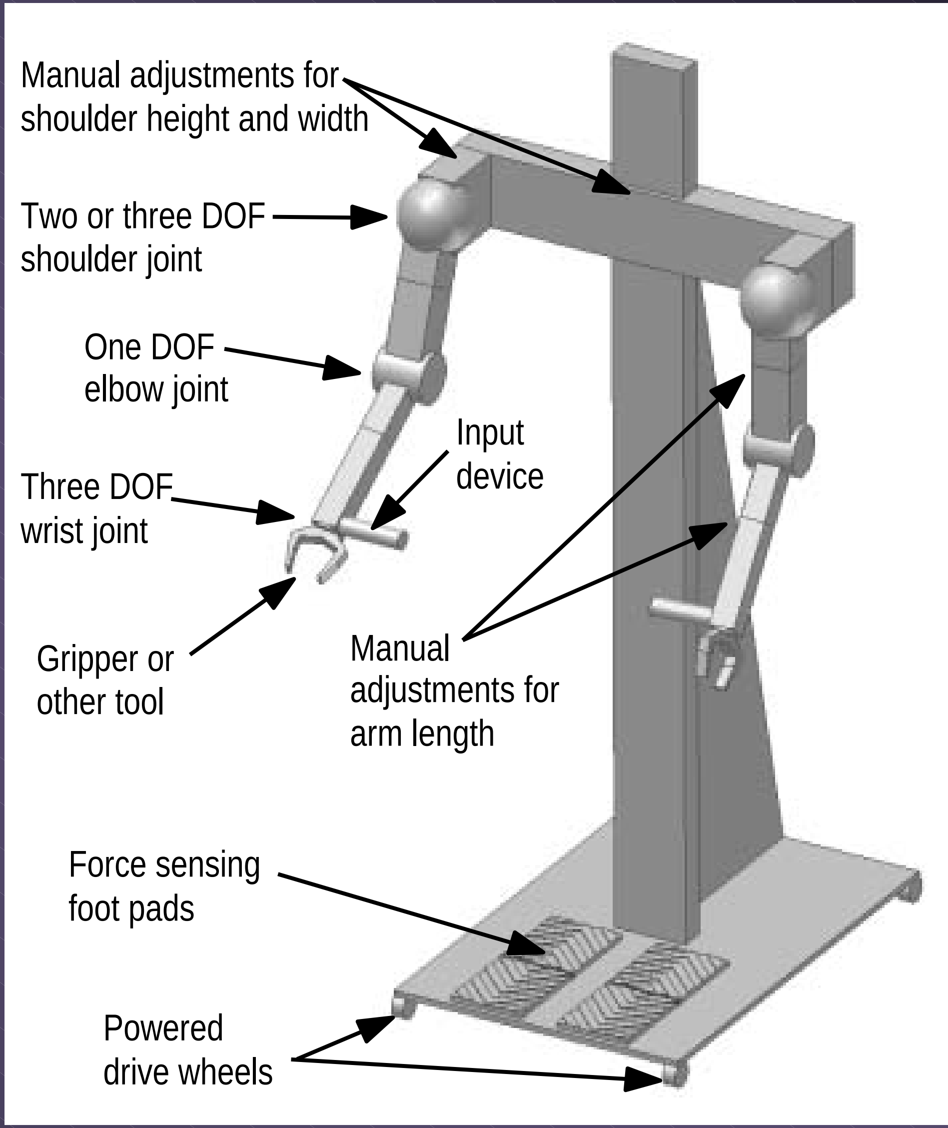
- PEX fall into two categories:
  - User interface devices for tele-robotics and virtual reality applications
  - Devices to amplify the user's force output.
- Our work belongs to the second category

Introduction (page 3)

- Related work:
  - The failed “Hardiman” project by GE (‘60s)
  - Work by Kazerooni’s group at U.C. Berkeley (‘90s to present).
  - Yamamoto *et al*. (2000), Rosen *et al.* (2001), and Kiguchi *et al.* (2003).

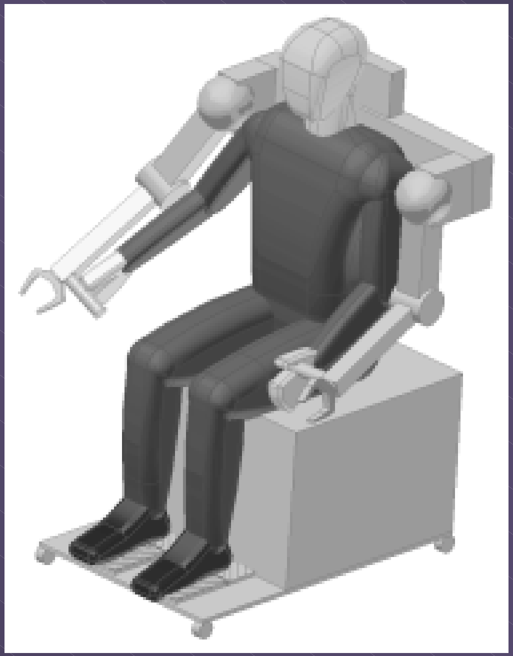
Design Concept

- PEX for factory use.
- Design features
- Shoulder DOF?
- Options for input device:
  - electromyogram (EMG) vs. force sensing
- Our goal is to reduce fatigue and to prevent injuries.
- Limit speed and power for comfort and safety.



Design Concept (page 2)

- Design specs:
  - Max. payload = 10 kg
  - Min. move time for full range of shoulder motion = 3 s
  - Min. move time for full range of elbow motion = 1.5 s



Kinematics Analysis

- Focused on the three active DOF of the right arm of the PEX.
- Link lengths based on anthropometrical data.
- Derived a kinematic model using the standard D-H method and analyzed the Jacobian matrix for potential singularities.
- Singularities can lead to very high joint velocities and should be avoided.

Kinematics Analysis (page 2)

- Equation for the singularities:

$$a_2 d_4 \cos(\theta_3)\left(d_4 \sin(\theta_2+\theta_3) - a_2 \cos(\theta_2)\right) = 0$$

- **Case #1:** PEX-Arm is at a singularity whenever:

$$\theta_3 = 90° \text{ or } \theta_3 = 270°$$

- The motion range for the human elbow is:

$$130° < \theta_3 < 270°$$

- For user safety, and to avoid the singularity, we will restrict the movement range to:

$$140° < \theta_3 < 260°$$

Kinematics Analysis (page 3)

- **Case #2:** PEX-Arm is at a singularity whenever:

$$d_4 \sin(\theta_2 + \theta_3) - a_2 \cos(\theta_2) = 0$$

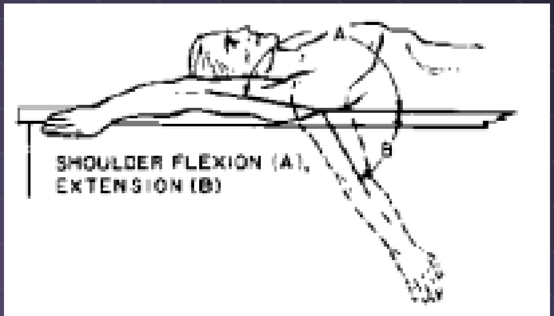
- The singularity can be avoided by dynamically restricting the joint angles such that:

$$d_4 \sin(\theta_2 + \theta_3) \neq a_2 \cos(\theta_2)$$

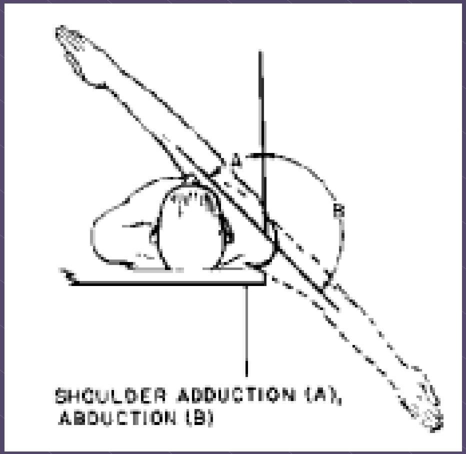
- However this solution will create a cylindrical workspace void with a centerline collinear with rotation axis of the first shoulder joint.
- This result is helpful for choosing which two of the human's three shoulder DOF should be assisted by the PEX-Arm.

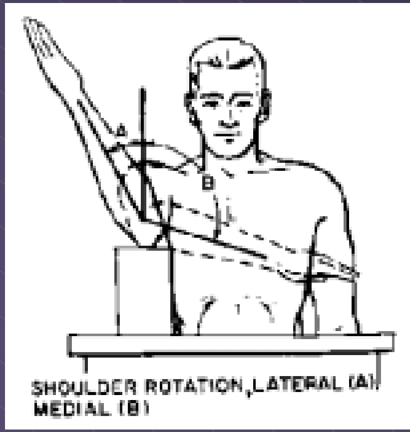
Kinematics Analysis and Shoulder DOF

- **Singularity Case #2 continued:**



- Need flexion-extension DOF to pick up objects.
- If the PEX-Arm assists the rotation lateral-medial DOF then the workspace void will be directly in front of the user at shoulder height.





- Assisting the adduction-abduction DOF will place the workspace void along the right-hand side of the user's body
- Only problem is no arm wrestling !

Dynamics Analysis

- Although pneumatic actuators are promising for future PEXs, for our first prototype DC motors with gearboxes will be used.
- To properly design the gear motors the velocity and torque requirements for each joint must be estimated.
- An approximate dynamic model has to be used since the masses of the gear motors are not known *a priori*.

Results of Dynamics Analysis

- The required torque has four components:
  - centripetal, Coriolis, inertial and gravitational.
- The centripetal and Coriolis components of the torque were insignificant.
- The arm configurations that maximized the inertial and gravitational components were determined for each joint.
- The maximum joint velocities were determined using the movement time specs.

Results of Dynamics Analysis (page 2)

- Estimated velocity, torque and power requirements:

Requirement	Shoulder Adduction-Abduction (Joint 1)	Shoulder Flexion-Extension (Joint 2)	Elbow Flexion (Joint 3)
Velocity (rad/s)	1.5	2.0	2.8
Torque (Nm)	6	100	62
Power (W)	10	200	170

Prototype Three DOF PEX-Arm

- Joint actuator design:
  - Motors should be 20 W, 250 W and 250 W
  - Present prototype uses three Maxon 150 W motors.
  - 900:1 gear reduction for shoulder DOF and 400:1 reduction for elbow DOF).
  - Dual-stage gearboxes were custom designed and built to be compact and lightweight.

Prototype Three DOF PEX-Arm (page 2)

- Control system design:
  - User input device is a custom made three DOF force sensing joystick
  - Control system has two levels.
  - At the higher level, the joystick output signals are converted into velocity setpoints for the lower level controllers.
  - At the lower level, the joint velocities are controlled using encoder feedback and standard PID control.

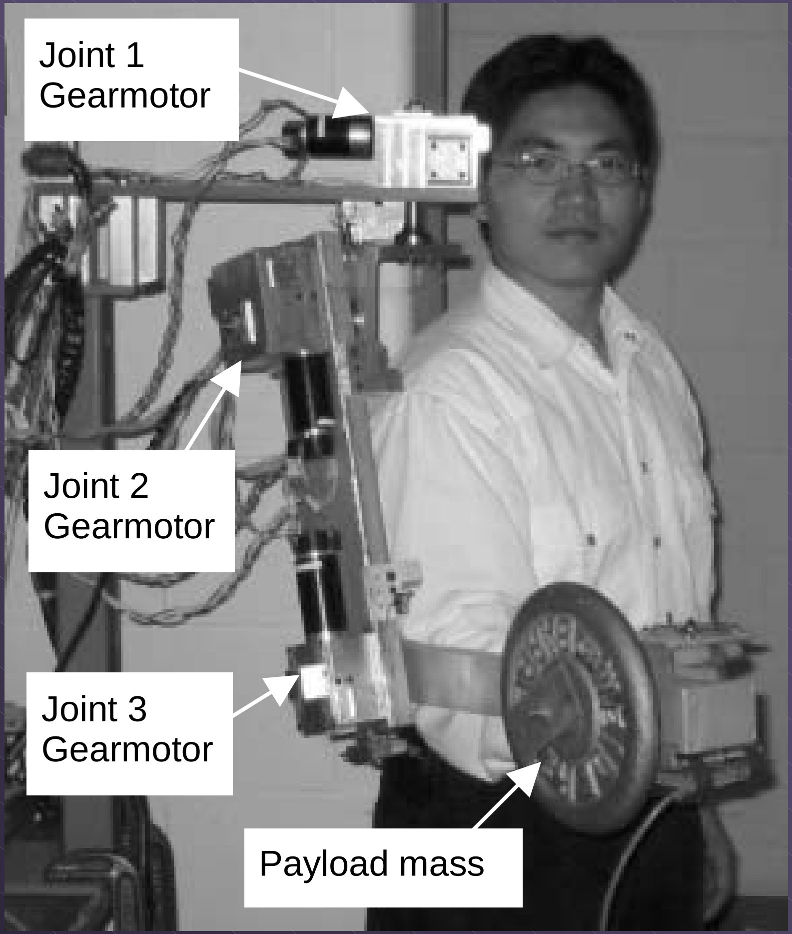
Prototype Three DOF PEX-Arm (page 3)

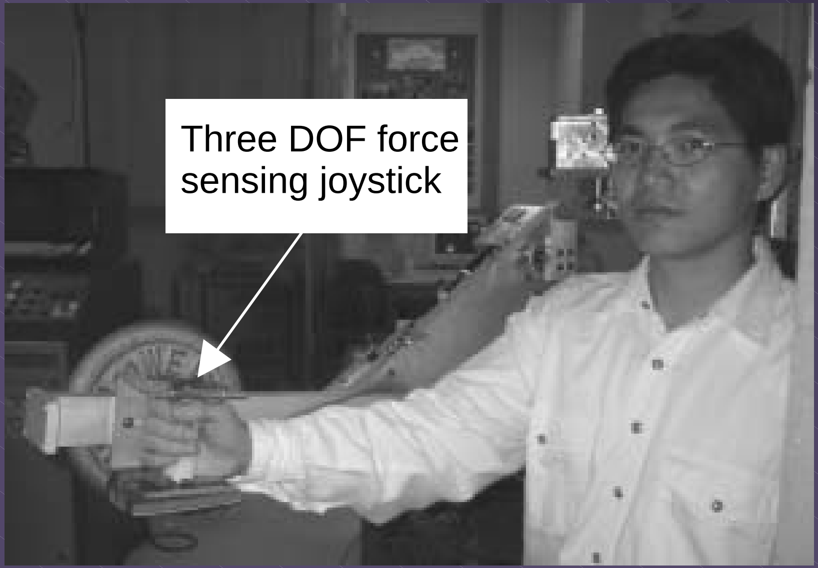
- Design of Safety Systems:
  - Speed and torque of the joints do not exceed human levels. <u>Physically limited by gear motor design rather than software limited.</u>
  - Gearbox is self-locking so the PEX-Arm won't fall if the power fails.
  - Joint angle limits are less than human motion range.

Prototype Three DOF PEX-Arm (page 4)

- Design of Safety Systems continued:
  - The user is not strapped into the PEX as is the case with other designs.
  - A three position (off, on, off) liveman switch will be incorporated soon.

Assembly and Testing





Assembly and Testing (page 2)

- Maximum payload tested to date is 5 kg
- With a 5 kg payload:
  - Max. endpoint velocity = 0.6 m/s
  - Max. joint velocities are 55 deg/s, 48 deg/s and 108 deg/s.
- Max. effective force amplification is 16:1
- Note that user cannot directly control the output force, only the velocity.

Video Demonstration