Multi Degree-of-Freedom Hydraulic Human Power Amplifier with Rendering of Assistive Dynamics

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Driven to Discover℠

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Human Power Amplifier

- Tool that amplifies human force: in oar form
  - Another example: exoskeleton
- Control objective: passive mechanical tool
  - Physically connected to the task
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Control Objective

- Controlling the hydraulic actuator force

\[ M_p(q)\ddot{q} + C_p(\dot{q}, q)\dot{q} + G_p(q) = F_{human} + F_{env} + F_a \]

- **Amplify** the human force by a factor of \((\rho + 1)\)
  - resulting in the dynamics of target passive mechanical tool:

\[ M_L(q)\ddot{q} + C_L(\dot{q}, q)\dot{q} + G(q) = (\rho + 1)F_{human} + F_{env} + F_{guide} \]

- **\(M_L\)**: apparent inertia of the tool
  - Achieved when \(F_a = \rho F_{human}\)
Hydraulic Transformer

- Hydraulic: high power density, precision, compactness

- Pressure control by metering valve causes a significant throttling losses
  - Heat generation

- Transformer eliminates such losses
  - Constant power between input A’ and load B

Can we use transformer for human power amplifier?
Outline

• Introduction
• System Dynamics
• Control Strategy
  • Virtual coordination approach
  • Guidance Control
• Experimental Results
• Conclusion
System Description

- Generalized coordinate
  \[ M_p(q)\ddot{q} + C_p(\dot{q}, q)\dot{q} + G_p(q) = F_{human} + F_{env} + F_a \]

- Hydraulic force from cylinder and motor
  \[ F_a = \begin{bmatrix} T_\theta \\ F_x \end{bmatrix} = \begin{bmatrix} J_A(\theta_p) & 0 \\ 0 & \frac{1}{r_m} \end{bmatrix} \begin{bmatrix} F_\theta \\ T_x \end{bmatrix} \]

- Cylinder for pitch
  \[ F_\theta = P_\theta A_1 - P_T A_2 \]

- Motor for reach
  \[ T_x = P_x \frac{D_m}{2\pi} \]
  \[ \dot{P}_\theta = \frac{\beta(P_\theta)}{V_1(x_\theta)} \left( Q_\theta - A_1 \dot{x}_\theta \right) \]
  \[ \dot{P}_x = \frac{\beta_e(P_x, P_{m1})}{V_m} \left( Q_x - \frac{D_m}{2\pi r_m} \dot{x}_p \right) \]
  \[ V_1(x_\theta) = V_{10} + A_1 x_\theta \]

- Connected to a transformer
Virtual Coordination Approach

- Direct Force control [1] \( \tilde{F} = F_a - F_d \rightarrow 0 \)
  - Positive velocity feedback effect
  - Not robust

Virtual Coordination Approach

• Direct Force control [1] \( \tilde{F} \to 0 \)
  • Positive velocity feedback
  • Not robust

• Virtual coordination approach [2]

• Hydraulic actuator = ideal kinematic actuator in series with nonlinear spring
  • Compressibility

• Design controller to mimic the mass-spring system
  • Virtual + Actual


Virtual System

- Virtual inertia acts with \[ M_v \ddot{q}_v = F_d - F_a + w + F_{guide} \]

- If coordinated \[ \dot{q}_v(t) \equiv \dot{q}(t) \] then resulting dynamics is

\[
(M_V + M_p(q))\ddot{q} + C_p(\dot{q}, q)\dot{q} = \\
(\rho + 1)F_{human} + F_{env} + F_{guide}
\]

- The target dynamics!

- Guidance

\[
\int_0^t [\dot{q}^T F_{guide}] d\tau \leq c_g^2
\]

- Passivity:

\[
\int_0^t \dot{q}^T [(\rho + 1)F_{human} + F_{env}] d\tau \geq -c^2
\]
Passive Decomposition - Transformation

- Transformation into the velocity spaces [5]

\[
\begin{bmatrix}
V_L \\
V_E
\end{bmatrix} = \begin{bmatrix}
I - \phi & \phi \\
I & -I
\end{bmatrix} \begin{bmatrix}
\dot{\phi} \\
\dot{q}_v
\end{bmatrix}
\]

\[
\phi = \frac{M_v}{M_L}
\]

\[
M_L = M_v + M_p
\]

\[
M_E = \left(\frac{1}{M_v} + \frac{1}{M_p}\right)^{-1}
\]

Center of the mass of combined system

Coordination error

• Transformed dynamics:

Locked System

\[
M_L(q)\dot{V}_L + C_L(\dot{q}, q)V_L + C_{LE}(\ddot{q}, q)V_E = F_d + F_{env} + F_{human} + w + F_{guide}
\]

Shape System

\[
M_E(q)V_E + C_E(\dot{q}, q)V_E + C_{EL}(\ddot{q}, q)V_L = F_a + \underbrace{\phi(F_{env}) + \phi(F_{human})}_{F_{E1}} - \underbrace{(I - \phi)(F_d + w + F_{guide})}_{F_{E2}}
\]

• Then, design controller for shape system to make sure \(V_E \to 0\)!

PVFC and Obstacle Avoidance

- Using the virtual coordination scheme, we can add some additional control to the virtual system such that the physical system will be naturally guided.
Experimental System

- 2-DOF Human Power Amplifier with a force handle
- Cylinder driven by transformer

Computer controlled variable transformer prototype based on 3.5cc micro-piston pumps
Human Power Amplification

- Wrestling $\rho = 11$

Added force input

RMS $\sim 3\%$ with mean desired force

- Force [N]
  - Actual
  - Desired

- Velocity [m/s]
  - Actual
  - Virtual

RMS 0.0094 m/s
PVFC + Obstacle Avoidance

- Obstacle Avoidance + PVFC

\[ \rho = 7 \]
Other developments in Transformer

- Demonstrated controller performance
  - Trajectory tracking shown in FPMC 2015
  - HPA control shown in DSCC 2015, 2016

- Desire to show efficiency benefit experimentally

- Hardware-In-the-Loop?
Conclusion

- 2-DOF Passive velocity coordination control using a transformer
- PVFC and Obstacle Avoidance to assist the human operator
- Demonstrates transformer need not sacrifice control performance
- Transformer efficiency will be shown