A Robust Hybrid Intelligent Position/Force Control Scheme for Cooperative Manipulators

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Talk Overview

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- ➔ Problem Statement
- ➔ Standard Adaptive Control of CR
- ➔ Adaptive Fuzzy Controllers
- ➔ A Hybrid Adaptive Control Scheme
- ➔ Conclusions
- ➔ Future Research Directions

Introduction

Why Cooperative Robots?

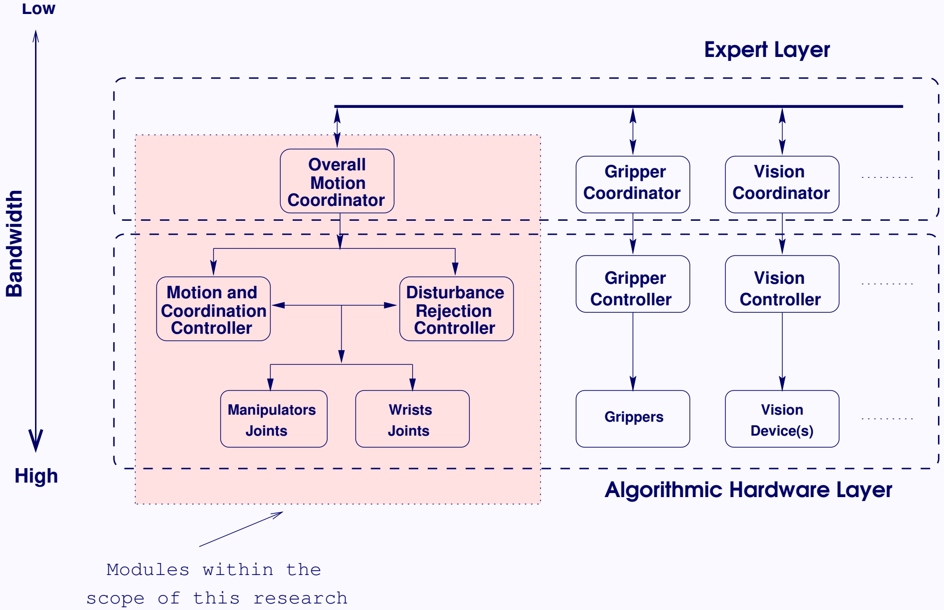
- More efficient handling of certain objects
  - Cardboards
  - Large sheets of glass
  - Heavy and/or large objects, in general
- Certain tasks may be too complex for a single manipulator system
  - Space missions
  - Underwater oil pipelines maintenance

Introduction (cont'd)

Research Scope

Although cooperative robots usually consist of several modules, the main focus here is on:

- Position and force control, and
- External disturbance attenuation.



Introduction (cont'd)

Challenges of CR Control

- Not much research done in the control of strongly coupled CR.
- Control of strongly coupled CR is much more complex than that of single robotic systems:
  - Kinematic and dynamic coordination.
  - Ubiquitous presence of uncertainties.
  - Stricter stability criteria.

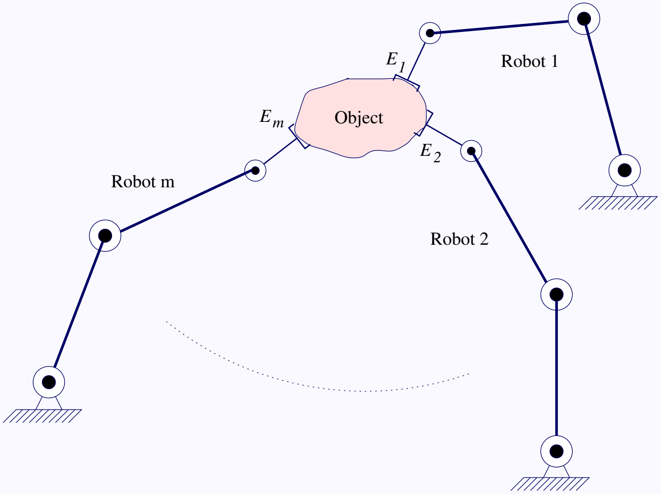
➠ Necessity to develop robust control approaches to keep up with the increasingly demanding design requirements.

Introduction (cont'd)

Brief History of CR Control

Types	**Main References**	**Shortcomings**
Non-adaptive	Tarn et al. 87, 88, 92 Bergerman et al. 98	✦ No control on internal forces. ✦ Model based: no uncertainties.
Adaptive	Hu et al. 93 Vukobratovic et al. 98 Liu et al. 98 Sun et al. 02 Szewczyk et al. 02	✦ No modeling uncertainties.
Soft computing	Ge et al. 99	✦ No control on internal forces. ✦ Neural network ➠ too many parameters. ✦ Controller's behavior not well understood.

Problem Statement



- ✯ Consider two or more cooperative manipulators holding a common object.

- ✯ Control Objectives:
  - ✦ Simultaneously
    - ➢ Track predefined object's trajectory (position and orientation.)
    - ➢ Make internal forces converge to desired values.
  - ✦ In the presence of
    - ➢ Parametric (structured) uncertainties (e.g., load's mass and inertia.)
    - ➢ Modeling (unstructured) uncertainties (e.g., unknown time-varying external disturbances.)

CR Dynamics

In a CR system, the ith manipulator's dynamics may be expressed as

$$\tau_i = D_i(q_i)\ddot{q}_i + C_i(q_i, \dot{q}_i)\dot{q}_i + G_i(q_i) - \tau_{d_i} - J_{\phi_i}^T(q_i) f_i$$

q_i : joint coordinates

τ_i : joint torque/force applied by actuator (controller's output)

τ_{d_i} : disturbance vector

$J_{\phi_i}(q_i)$: Jacobian matrix from payload's center of mass to q_i

f_i : internal force between end-effector and payload

$D_i(q_i)$: inertial matrix including payload's inertia

$C_i(q_i, \dot{q}_i)$: Coriolis and centrifugal matrix including payload's terms

$G_i(q_i)$: Gravitational vector including payload's gravitational terms

Standard Adaptive Control of CR

- ✯ One of the most recent and efficient CACs was proposed by Liu et al.
  Control law of ith manipulator:

$$\tau_i = \hat{D}_i(q_i)\ddot{q}_{r_i} + \hat{C}_i(q_i,\dot{q}_i)\dot{q}_{r_i} + \hat{G}_i(q_i) - K_{s_i}s_i - J_{\phi_i}^T(q_i)(K_i\tilde{x} + f_{d_i})$$

$\hat{A}$: estimate of matrix A with parametric uncertainties only
$\tilde{x} = x - x_d$: position error of the payload's center of mass
$\dot{q}_{r_i} = J_{\phi_i}^{+}(q_i)(\dot{x}_d - \gamma_i\tilde{x})$: the reference joint velocity
$s_i = \dot{q}_i - \dot{q}_{r_i}$: residual error of the reference joint velocity
$J_{\phi_i}^{+}(q_i)$: pseudo-inverse of $J_{\phi_i}(q_i)$
f_{d_i} : desired internal force
K_{s_i} and K_i : positive definite gain matrices

- ✦ Compensates for parametric uncertainties only.
- ✦ Assumes perfect knowledge of the working environment model.
- ➠ No compensation for modeling uncertainties nor for unstructured external disturbances.

Standard Adaptive Control of CR (cont'd)

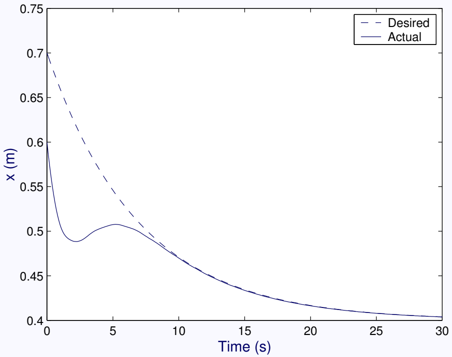
Numerical Results

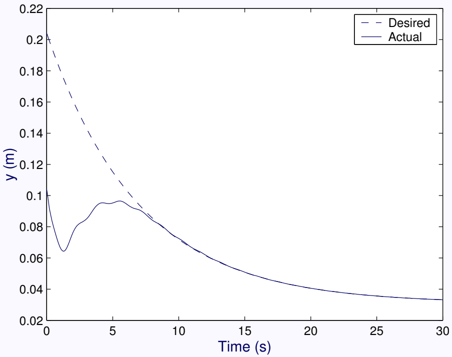
- Two 3-DOF manipulators.
- Payload to follow an oblique line between the two manipulators.
- Internal forces lines of actions are **not** orthogonal to payload's trajectory, with desired values $f_{d_1} = -f_{d_2} = 10$ N.
- $\tau_{d_1} = \alpha(\Gamma \dot{q}_1 + \rho(t) + \lambda)$, $\tau_{d_2} = -\alpha(\Gamma \dot{q}_2 + \rho(t) + \lambda)$

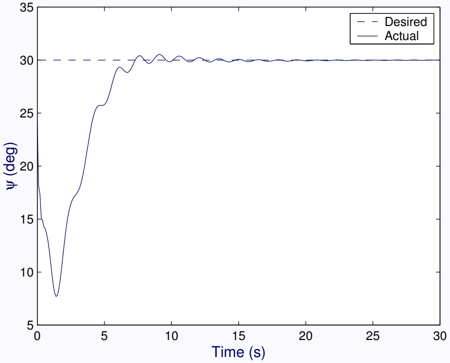
Standard Adaptive Control of CR (cont'd)

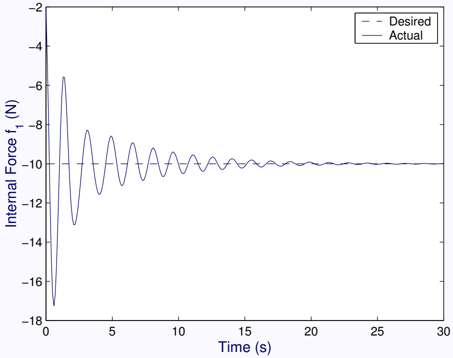
Experiment 1

- Parametric uncertainties only (payload's mass).
- No modeling uncertainties and no unstructured external disturbances ($\alpha = 0$).





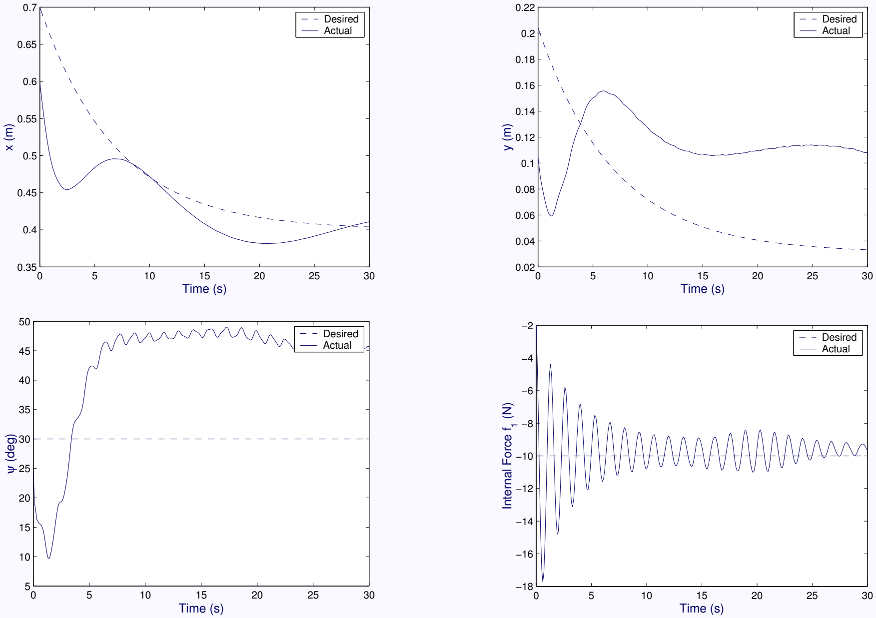




Standard Adaptive Control of CR (cont'd)

Experiment 2

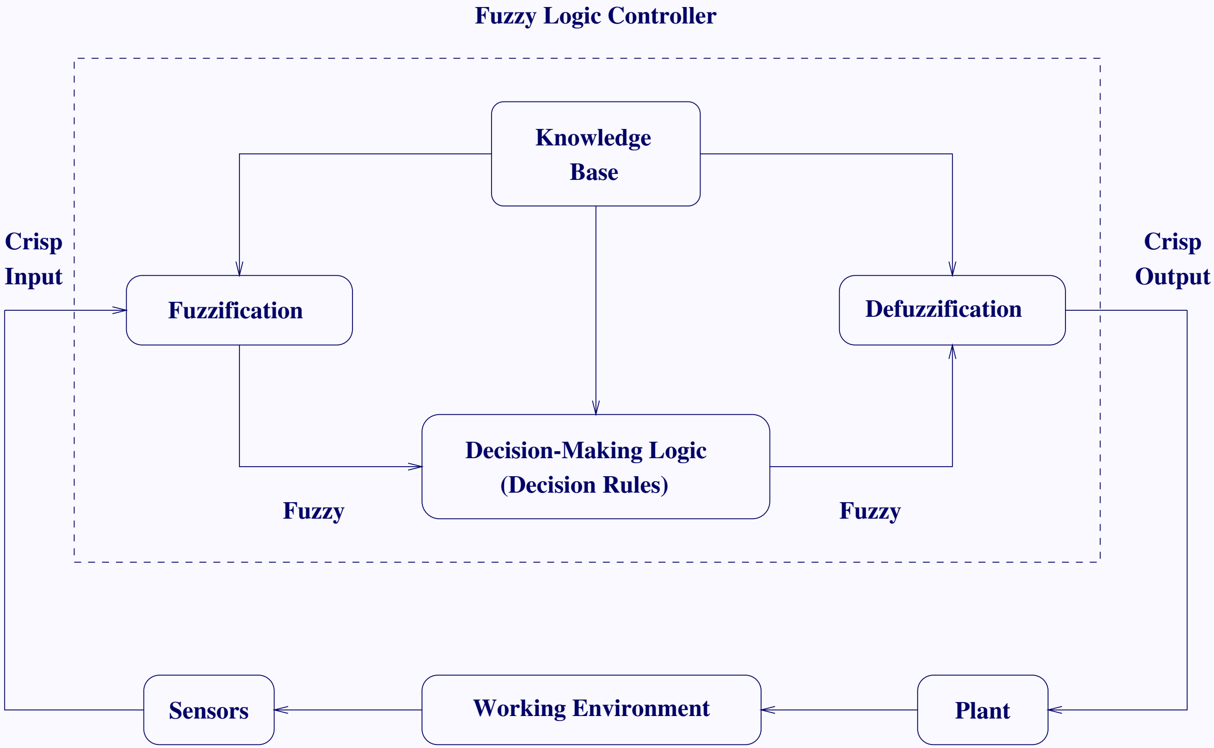
- Modeling uncertainties are introduced in the form of unknown time-varying external disturbances (intensity level $\alpha = 1$)



Soft Computing Based Controllers

- ✯ CR usually have very complex dynamics.
  ➠ deriving a precise model is extremely difficult.
- ✯ Soft computing tools do not require a precise dynamics model.
- ✯ Main focus here: fuzzy logic based controllers (FLCs.)
  - ✦ Rule-based expert systems: use of human-like linguistic variables, values, and simple if-then rules.
  - ✦ Powerful in representing human knowledge.

Soft Computing Based Controllers (cont'd)



Soft Computing Based Controllers (cont'd)

Merits of FLCs

- No need for a precise model.
- Robustness: tolerate noise and time-varying parameters in the plant's dynamics.
- Generic: can be transferred from one platform to another with minor modifications.

Drawbacks of FLCs

- heavily dependent on human expertise.
- Lack of efficient and systematic online adaptation mechanism to adapt to varying working conditions.

Adaptive Fuzzy Controllers

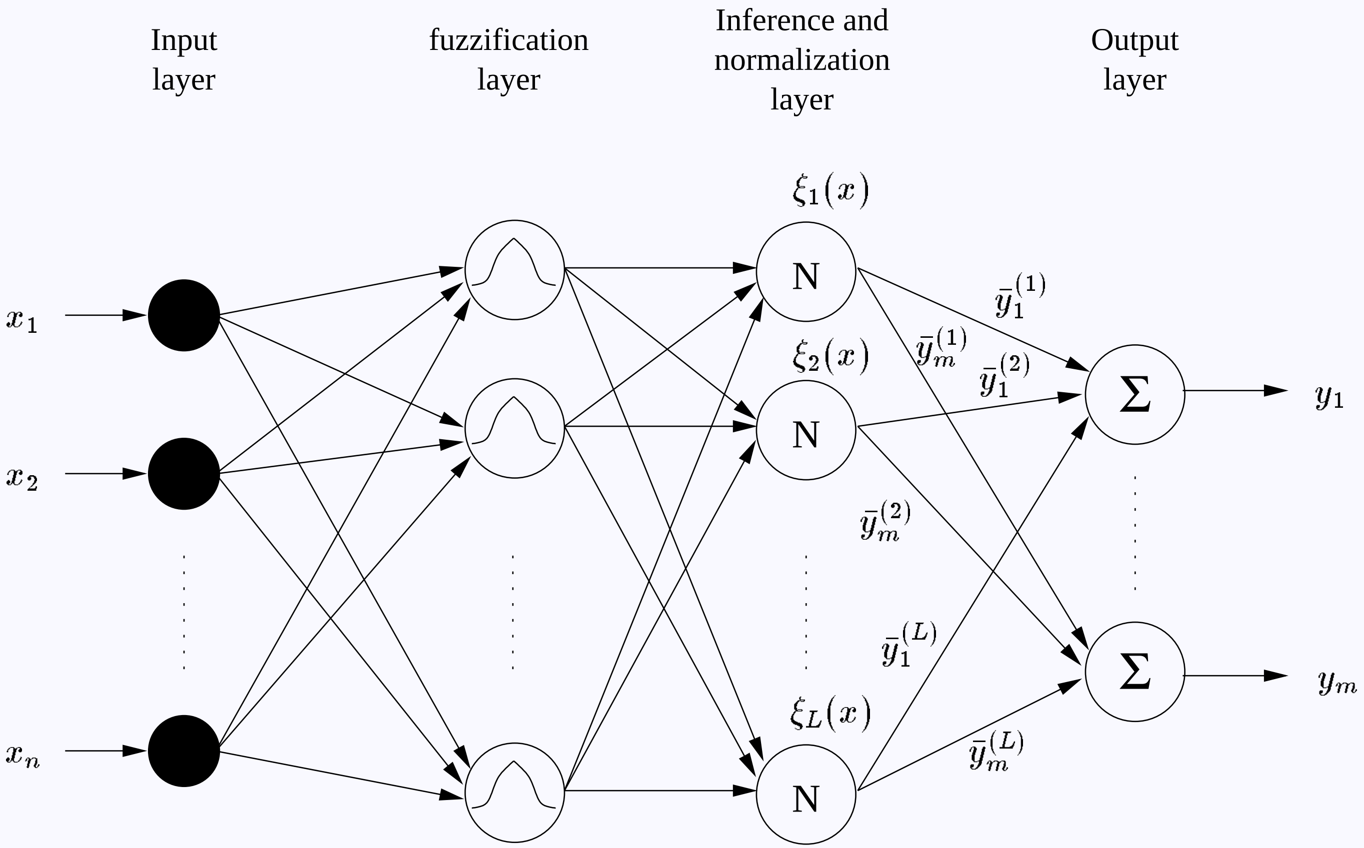
- Adaptive fuzzy controllers (AFCs) compensate for the shortcomings of static FLCs while inheriting their strengths.
  - Adaptation: ability to learn plant's dynamics online.
  - Higher robustness than CACs in the face of parametric and modeling uncertainties.
- Adaptive fuzzy controller's jth output:

$$y_j = \sum_{l=1}^{L} \bar{y}_j^{(l)} \xi_l(x) = \Theta_j^T \xi(x)$$

$$\Theta_j^T = (\bar{y}_j^{(1)}, \ldots, \bar{y}_j^{(L)}) \ , \ \xi^T(x) = (\xi_1(x), \ldots, \xi_L(x))$$

$$\xi_l(x) = \frac{\prod_{i=1}^{n} \mu_{A_i^{(l)}}(x_i)}{\sum_{k=1}^{L} \left(\prod_{i=1}^{n} \mu_{A_i^{(k)}}(x_i) \right)}, \quad l = 1, \ldots, L.$$

Adaptive Fuzzy Controllers (cont'd)



A Hybrid Adaptive Control Scheme

Let A^* denote the best possible approximation of matrix A in the face of parametric uncertainties.

Then A's modeling error can be expressed as $\bar{A} = A - A^*$.

Hence, the ith manipulator control law may be reformulated as:

$$\tau_i = \underbrace{\hat{D}_i^*(q_i)\ddot{q}_{r_i} + \hat{C}_i^*(q_i, \dot{q}_i)\dot{q}_{r_i} + \hat{G}_i^*(q_i) - K_{s_i}s_i - J_{\phi_i}^T(q_i)(K_i\tilde{x} + f_{d_i})}_{\tau_i^{(c)}}$$

$$+ \underbrace{\bar{D}_i(q_i)\ddot{q}_{r_i} + \bar{C}_i(q_i, \dot{q}_i)\dot{q}_{r_i} + \bar{G}_i(q_i) - \bar{\tau}_{d_i}}_{\tau_i^{(f)}}$$

$\tau_i^{(c)}$: CAC's torque output (parametric uncertainties only)

$\tau_i^{(f)}$: **supervisory** adaptive fuzzy regulator operating at a higher hierarchical level (**lower** bandwidth) than that of the CAC.

$\tau_i^{(f)}$ is modeled as an AFC ➠ $\tau_i^{(f)} = \hat{U}_i(q_i, \dot{q}_i, \dot{q}_{r_i}, \ddot{q}_{r_i} | \Theta_i)$

A Hybrid Adaptive Control Scheme (cont'd)

AFC's Computational complexity

$\tau_i^{(f)} = \hat{U}_i(q_i, \dot{q}_i, \dot{q}_{r_i}, \ddot{q}_{r_i} | \Theta_i)$

- ✦ 4 input vectors
- ✦ k_i DOF for manipulator i
- ✦ κ_i membership functions to fuzzify each input element
- ➠ Total number of fuzzy rules fired by the AFC at manipulator i is $L_i = (\kappa_i)^{4k_i}$

For $\kappa_i = 5$ and $k_i = 3$ ➠ $L_i = 244,140,625$ (too large!)

A Hybrid Adaptive Control Scheme (cont'd)

Rule Decomposition Scheme

- Idea: aggregate $\hat{U}_i(q_i, \dot{q}_i, \dot{q}_{r_i}, \ddot{q}_{r_i}|\Theta_i)$ into several MIMO AFCs:

$$\tau_i^{(f)} = \overbrace{\bar{D}_i(q_i)\ddot{q}_{r_i} + \underbrace{\bar{C}_i(q_i, \dot{q}_i)\dot{q}_{r_i} + \bar{G}_i(q_i) - \bar{\tau}_{d_i}}_{\hat{U}_i^2(q_i,\dot{q}_i,\dot{q}_{r_i})}}^{\hat{U}_i(q_i,\dot{q}_i,\dot{q}_{r_i},\ddot{q}_{r_i}|\Theta_i)}$$

- Unknown time-varying jth column of $\bar{D}_i(q_i)$ can be approximated by a MIMO AFC $\hat{U}_{ij}^1(q_i|\Theta_{ij}^1)$.
  - ➠ $\bar{D}_i(q_i)\ddot{q}_{r_i} \approx \sum_{j=1}^{k_i} \hat{U}_{ij}^1(q_i|\Theta_{ij}^1)\ddot{q}_{r_{ij}}$.
- $\dot{q}_{r_i}$ is dependent on q_i
  - ➠ $\hat{U}_i^2(q_i, \dot{q}_i, \dot{q}_{r_i})$ can be replaced by $\hat{U}_i^2(q_i, \dot{q}_i|\Theta_i^2)$.
- The torque offset generated by the **supervisory** adaptive fuzzy regulator module is:

$$\tau_i^{(f)} = \sum_{j=1}^{k_i} \hat{U}_{ij}^1(q_i|\Theta_{ij}^1)\ddot{q}_{r_{ij}} + \hat{U}_i^2(q_i, \dot{q}_i|\Theta_i^2)$$

A Hybrid Adaptive Scheme (cont'd)

▮ Computational Complexity

- ✦ Each $\hat{U}^1_{ij}(q_i|\Theta^1_{ij})$ fires $L^1_{ij} = (\kappa_i)^{k_i}$ rules.
- ✦ Number of rules fired by $\hat{U}^2_i(q_i, \dot{q}_i|\Theta^2_i)$ is $L^2_i = (\kappa_i)^{2k_i}$.
- ✦ Hence, the total number of rules fired by the AFC is $L_i = k_i(\kappa_i)^{k_i} + (\kappa_i)^{2k_i}$ for each robot.
  - ☞ Only $[(\kappa_i)^{k_i} + (\kappa_i)^{2k_i}]$ of them have different firing strengths $(\ll (\kappa_i)^{4k_i})$.
- ✦ For $\kappa_i = 5$ and $k_i = 3$ ➠ number of distinct firing strengths to be computed for each robot is $15,750$ ($\ll 244,140,625$).

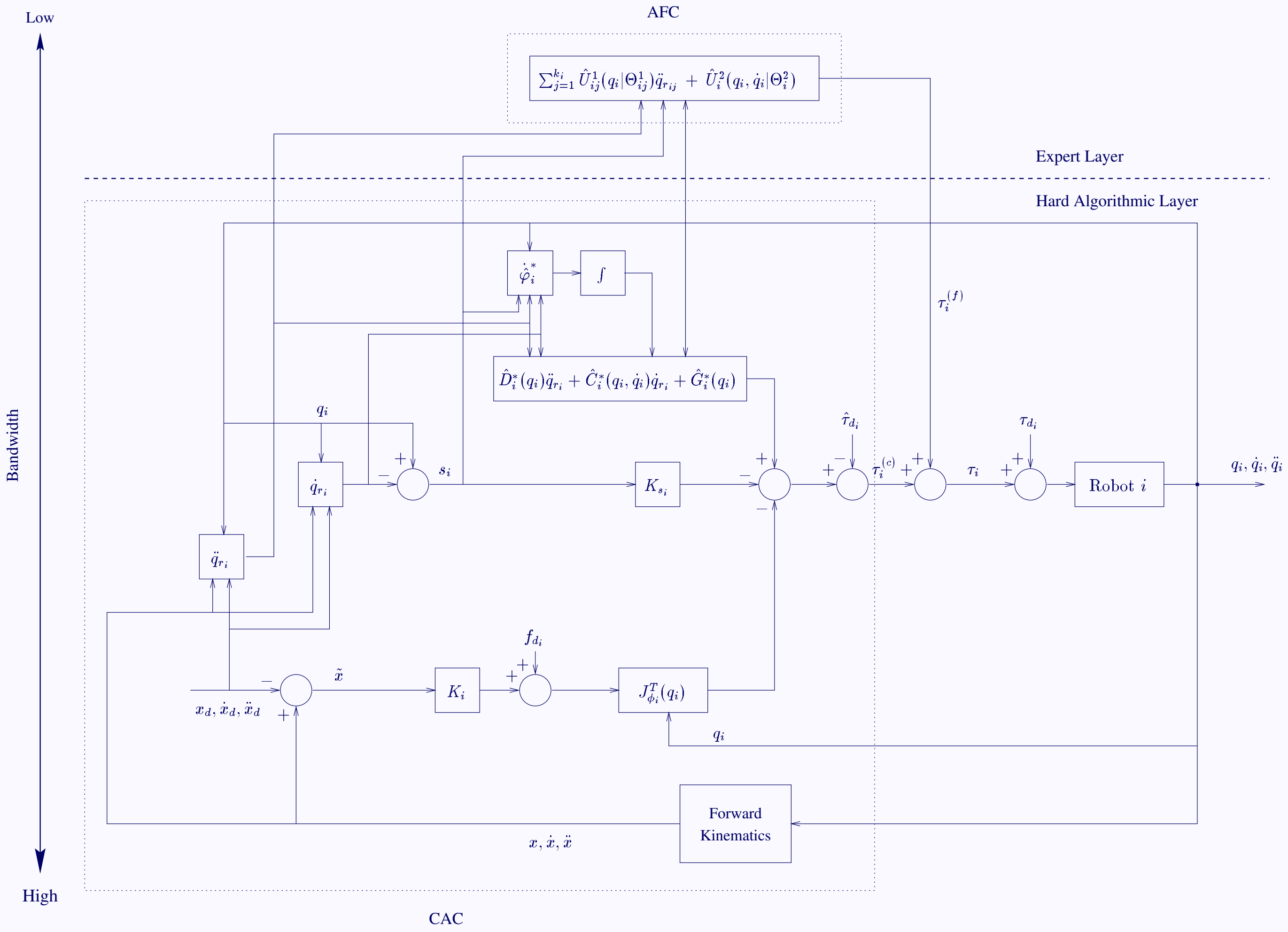
Theorem 1 *If the controller's gains satisfy the required constraints, then the HIC gives rise to an asymptotic convergence of the payload's position and the internal forces tracking errors, $\tilde{x}$ and $\tilde{f}_i$, to zero.*

A Hybrid Adaptive Scheme (cont'd)

Numerical Results

- 5 Gaussian membership functions are used to fuzzify each input of the AFC module of the HIC.
- AFC module has no prior knowledge of the manipulators dynamics (i.e., Θ^1_{ij} and Θ^2_i are initially set to zero for $i = 1, 2$ and $j = 1, \ldots, k_i$).
- 50% of the manipulators dynamics model is assumed to be known (for CAC.)
- For better computational efficiency, the supervisory adaptive fuzzy regulator module of the HIC is set to operate at a bandwidth 4 times lower than that of the CAC.

A Hybrid Adaptive Scheme (cont'd)

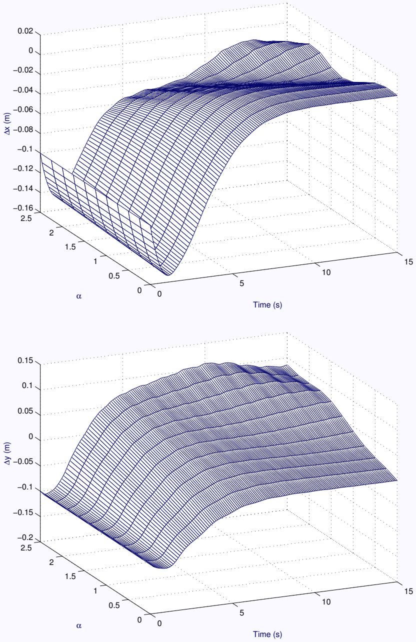


A Hybrid Adaptive Scheme (cont'd)

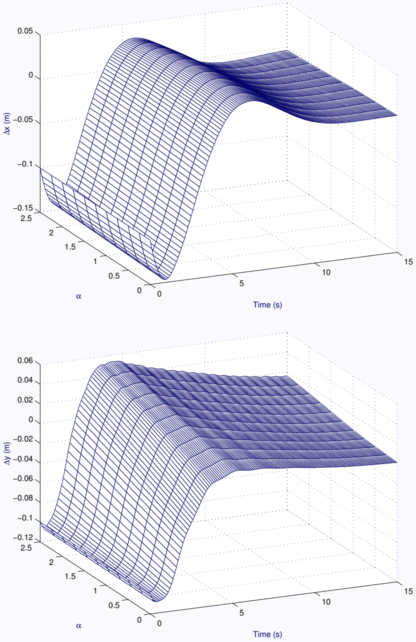
Experiment

- Intensity level of modeling uncertainties is varied by letting α span the interval $[0, 2.5]$.

CAC's Tracking Error

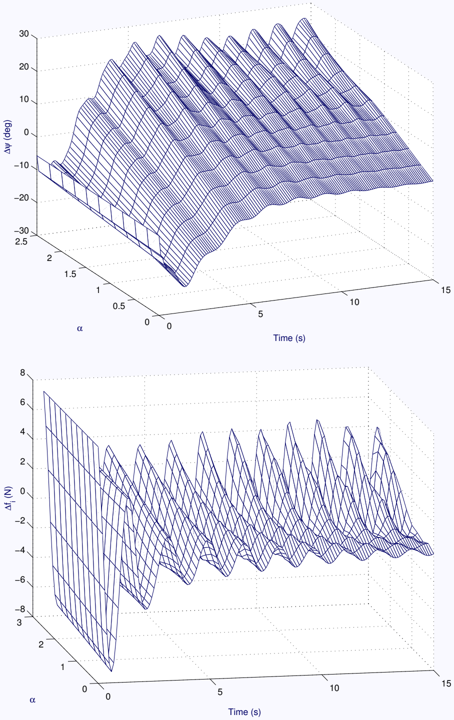


HIC's Tracking Error

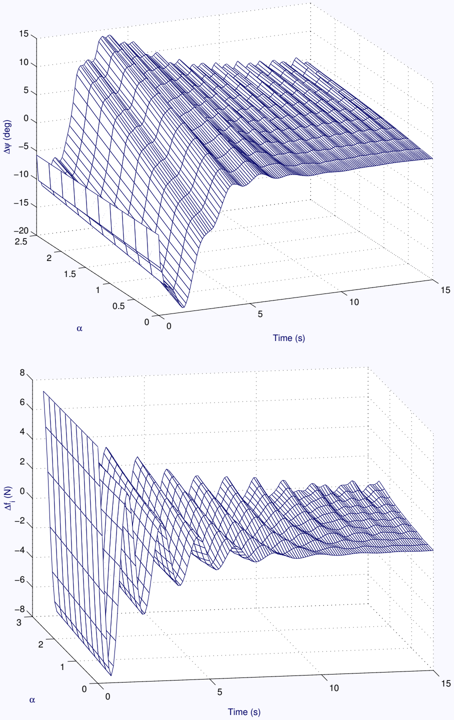


A Hybrid Adaptive Scheme (cont'd)

CAC's Tracking Error



HIC's Tracking Error



Conclusions

- ✯ Complex problem of controlling closed kinematic chain mechanisms: kinematic and dynamic coordination.
- ✯ Most adaptive controllers show success in the face of parametric uncertainties only.
- ✯ A novel hierarchical knowledge-based control scheme is proposed for the control of CR.
- ✯ Innovative rule reduction technique is presented to significantly reduce the computational complexity.
- ✯ First attempt to control CR in the face of both structured and unstructured uncertainties.

Conclusions (cont'd)

- Key characteristics of proposed hierarchical knowledge-based controller:
  - Robustness in the face of parametric and modeling uncertainties of varying intensity levels.
  - Both, position and internal force tracking errors are proven to converge to zero.
  - Generic: easily portable from one platform to another (minor tunings may be needed.)

Future Research Directions

- ✯ Allow the automatic tuning of antecedent membership functions.
- ✯ Extend the zero-order Sugeno-type AFC to a first-order one: potential of higher approximation capabilities.
- ✯ Extend the FLC model to a type-2 FLC to improve controllers robustness.