A Non-Invasive, Real-Time Method for Measuring Variable Stiffness

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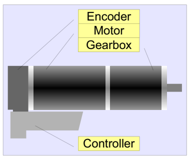
A Recent Evolution in Robotic Actuation

Traditional (rigid) Servomotors



Schematic drawing of a typical servomotor used for industrial applications.

A set of VSAs (Variable Stiffness Actuators), realized in the interdepartmental research center “E. Piaggio”, University of Pisa. From left to right (and from old to new) the original prototype VSA 1, the more compact VSA 2 and the optimized and fully integrated VSA-HD.

Why Variable Stiffness?

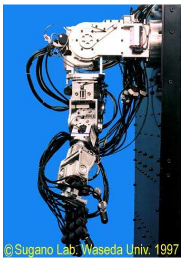
- Advantages
  - Safety / Performance trade-off optimization
  - Actuator Robustness
  - Adaptability to environment
  - Energy optimization
- Applications
  - Human-Robot Interaction
  - Rehabilitation
  - Gait locomotion
  - ...

Series Elastic Actuation

A SEA (Series Elastic Actuator) to be used as a robotic leg, realized from the Yobotics! company. Picture from: http://yobotics.com/actuators/actuators.htm

Fig. X: The problem of measuring stiffness arises also in psycho-physiological experiments and diagnostic procedures.

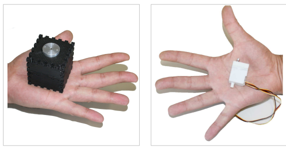
Mechanical Impedance Adjuster



A MIAs (Mechanical Impedance Actuators) powered arm, realized at Sugano Labs, Waseda University, in 1997. Picture from: http://www.sugano.mech.waseda.ac.jp/wendy/arm/mia1-e.html

A Variable Stiffness arm, realized by the Interdepartmental Research center “E. Piaggio”, in University of Pisa.

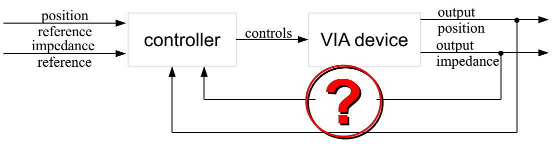
Variable Stiffness Actuation



The latest arrivals in the VSA family, the VSA cube-bots: new generation of highly integrated, general purpose and modular Variable Stiffness Actuators, from the interdepartmental research center “E. Piaggio”, University of Pisa.

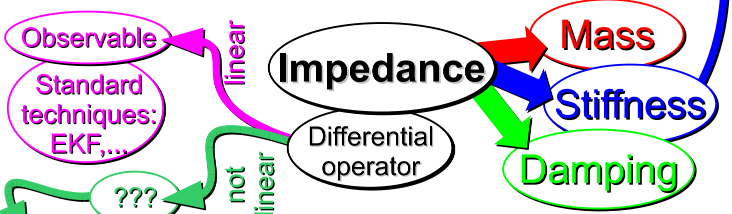
...towards Variable Impedance

- How to control VIA devices?



Online measurement needed for feedback! So...

- How to **Measure Impedance**?



Conclusion is not trivial without prior knowledge of a model!!!

Our Algorithm

A Stiffness Observer
- Non-linear
- Time-varying
- Model-independent
- Uniformly Ultimately Bounded Error

$$|\tilde{\sigma}| > \frac{|\sigma_y|}{\alpha} + \left(|s_u| + \frac{|\sigma_u|}{\alpha}\right) v$$

Error bound depends on ratio between speeds of stiffness variation and spring deflection:
Measuring Variable Stiffness has Intrinsic limitations:
e.g. Stiffness variation cannot be detected if the system is not moving

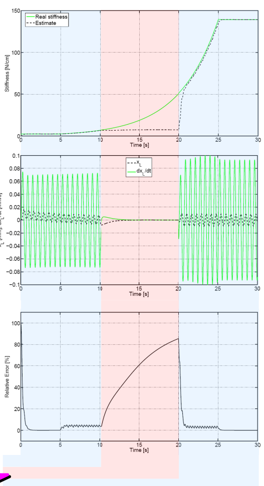
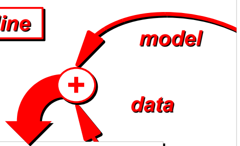


Fig. 9. Simulation results for the VSA system with exponential springs. a) Comparison of the link stiffness with its estimate; b) Relative estimation error; c) link motion during the simulated experiment.

Experiment

Off-line



Setup

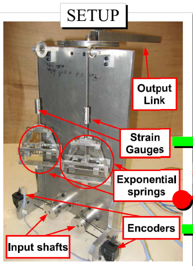


Fig. 10. The experimental setup consists of an antagonistic VSA system with exponential springs, realized using a linear spring forced to move on a suitable cam profile. Force sensors (strain gauges) are mounted on the tendons connecting the springs to the link. Position sensors (encoders) are mounted on the link and on two tendon pulleys coupled with the input levers.

Data Acquisition

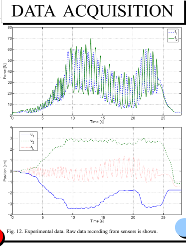


Fig. 12. Experimental data. Raw data recording from sensors is shown.

Characterization

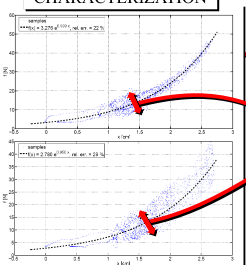


Fig. 11. Experimental characterization of the two exponential springs. Force and displacement pairs recorded during a calibration experiment, and regression curve are shown for each of the two springs of the experimental VSA system. The spring model is:

On-line

Impedance Observer

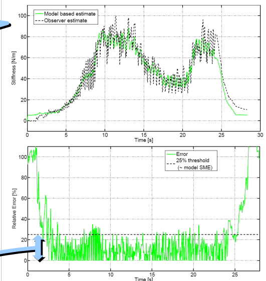
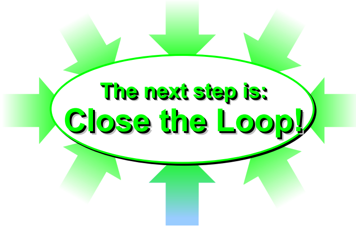


Fig. 13. Experimental results for the stiffness observer. The first panel shows a comparison between the stiffness values derived by the calibrated spring model and the estimate performed by the stiffness observer algorithm. The second panel shows the relative error (difference between estimate and model, normalized w.r.t. the model) compared with the relative error underlying the model itself.

Model uncertainty ≈ 25% ≈ **Observer error ≈ 25%**

REMARK: observer error is calculated with respect to the model



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