KTH ROYAL INSTITUTE OF TECHNOLOGY



# Introduction to Robotics

Lecture 5 - Actuators, Sensors I





# Assignment 1 - (ROS Basics)

- P/F.
- presented to the TA's during regular lab hours
- Presentation by Fri 10th of September gives 3 bonus points

# Assignments 2-4 - (Kinematics, Planning, and Mapping)

- E/C
- submitted to the Kattis autograder
- different requirements for E or C, see each assignment for details.
- E by the deadlines is awarded with 3 bonus points.
- C by the deadlines is awarded with 2 additional bonuspoints.

Maximum possible bonus for completing all three assignments on time:  $(3^*(3+2)) = 15$  bonus points.



Kattis is the autograding system used by the EECS school. It is used for assignments 2, 3, and 4 in this course.

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**Kattis** 

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#### Schedule - Lectures

Aug 30 - 1. Intro, Course fundamentals, Topics, What is a Robot, History, Applications.

- Aug 31 3 ROS Introduction
- Aug 31 2 Manipulators, Kinematics
- Sep 07 4. Differential kinematics, dynamics
- Sep 09 5. Actuators, sensors I (force, torque, encoders, ...)
- Sep 12 6. Grasping, Motion, Control
- Sep 14 7. Planning (RRT, A\*, ...)
- Sep 19 8. Behavior Trees and Task Switching
- Sep 21 9. Mobility and sensing II (distance, vision, radio, GPS, ...)
- Sep 26 10. Localisation (where are we?)
- Sep 28 11. Mapping (how to build the map to localise/navigate w.r.t.?)
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Oct 05 - Q/A - Open questions to your teachers.



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$$\tau = J^T \mathcal{F}$$

 We can now see that for singular configurations, there will be directions where the required torque for a given force goes to zero, or inversely, the forces generated by a given torque tend to infinity. This may cause damage to the robot or the environment.



#### Dynamics (R-MPC Chapter 7)



$$I_{xx} = \iiint_{V} (y^{2} + z^{2})\rho dv,$$
  

$$I_{yy} = \iiint_{V} (x^{2} + z^{2})\rho dv,$$
  

$$I_{zz} = \iiint_{V} (x^{2} + y^{2})\rho dv,$$
  

$$I_{xy} = \iiint_{V} xy\rho dv,$$
  

$$I_{xz} = \iiint_{V} xz\rho dv,$$
  

$$I_{yz} = \iiint_{V} yz\rho dv,$$

## Dynamics



Outward iterations:  $i: 0 \rightarrow 5$ 

$$\begin{split} ^{i+1} \omega_{i+1} &= {}_{i}^{i+1} R^{i} \omega_{i} + \dot{\theta}_{i+1} \, {}^{i+1} \hat{Z}_{i+1}, \\ ^{i+1} \dot{\omega}_{i+1} &= {}_{i}^{i+1} R^{i} \dot{\omega}_{i} + {}_{i}^{i+1} R^{i} \omega_{i} \times \dot{\theta}_{i+1} \, {}^{i+1} \hat{Z}_{i+1} + \ddot{\theta}_{i+1} \, {}^{i+1} \hat{Z}_{i+1}, \\ ^{i+1} \dot{v}_{i+1} &= {}_{i}^{i+1} R ({}^{i} \dot{\omega}_{i} \times {}^{i} P_{i+1} + {}^{i} \omega_{i} \times ({}^{i} \omega_{i} \times {}^{i} P_{i+1}) + {}^{i} \dot{v}_{i}), \\ ^{i+1} \dot{v}_{i+1} &= {}^{i+1} \dot{\omega}_{i+1} \times {}^{i+1} P_{C_{i+1}} \\ &+ {}^{i+1} \omega_{i+1} \times ({}^{i+1} \omega_{i+1} \times {}^{i+1} P_{C_{i+1}}) + {}^{i+1} \dot{v}_{i+1}, \\ ^{i+1} F_{i+1} &= m_{i+1} \, {}^{i+1} \dot{v}_{C_{i+1}}, \\ ^{i+1} N_{i+1} &= {}^{C_{i+1}} I_{i+1} \, {}^{i+1} \dot{\omega}_{i+1} + {}^{i+1} \omega_{i+1} \times {}^{C_{i+1}} I_{i+1} \, {}^{i+1} \omega_{i+1}. \end{split}$$

Inward iterations:  $i: 6 \rightarrow 1$ 

$$i f_{i} = i_{i+1} R^{i+1} f_{i+1} + {}^{i} F_{i},$$
  

$$i n_{i} = {}^{i} N_{i} + i_{i+1} R^{i+1} n_{i+1} + {}^{i} P_{C_{i}} \times {}^{i} F_{i}$$
  

$$+ {}^{i} P_{i+1} \times i_{i+1} R^{i+1} f_{i+1},$$
  

$$\tau_{i} = {}^{i} n_{i}^{T \ i} \hat{Z}_{i}.$$



The resulting dynamic equations can be written on the form (state-space equation):

$$\tau = M(\Theta)\ddot{\Theta} + V(\Theta,\dot{\Theta}) + G(\Theta) + J^{T}f$$



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- Actuation
  - Motors, other types
  - Geometry, transmissions
  - Electronics
- Sensing
  - Proprioception
  - Forces/torques, tactile
  - Sensorless estimation



- Electric motors
  - Easy to control, very precise
  - Most common in robotic manipulators
- Pneumatics
  - Inherently compliant
  - Silent, non-magnetic
- Hydraulics
  - Very powerful
  - Good at static forces/torques



- Simple servo motors
- Cheap
- Go to commanded position







- Brushless motors
  - Good static torque, but may overheat
  - Torque decreases approx.
     linearly with rotational velocity
  - Available in wide range of power ratings, for a given design, peak output power is limited by heat.
  - Torque is proportional to current
  - 1~10 kW/kg







#### Actuation - electric motors

• Brushless motors + water cooling





- Stepper motors
  - Can be advanced in "ticks"
  - Typically makes a characteristic noise







- Hardware:
  - Each motor is driven by analog signals, and must be powered by a motor driver unit.





#### Image: TiTech motor driver v.2



• Pulse width modulation - PWM





- Pulse width modulation PWM
  - Typical frequencies for motors are in the 1~10 kHz range.
  - Motor acts as low-pass filter (inductor coil + mass)





- Direct drive is not always possible we need transmissions
- Typical reduction ratios are 50:1 ~ 300:1



- Transmission issues:
  - Motor inertia is multiplied by square of ratio, potentially largest dynamic factor

If gear ratio is **a**, and motor inertia around axis is  $I_a$ , the inertia  $I_i$  in the link frame will be

$$|| = a^{2} * ||_{a}$$



- Transmission issues:
  - Backlash



Image: Wikimedia - user Slashme



• Harmonic Drive - strain wave gearing (SWG)







#### Actuation

- Geometric design issues, placement of motors and drivers
  - Motors (+ gears) place mass further out in kinematic chain, requiring more power.
  - Cables
    - Each motor requires min. 2 cables (power)
    - Each driver requires min. 4 cables (power + data), but these can be shared
    - Difficult to pass multiple cables through joints



## Motor and driver placements







Image: KUKA



#### Motor and driver placements





- Torques can be measured as cable load.
- Cable may need retightening frequently

Image: Barrett Technology



- Pneumatics
  - Inherently compliant
  - Silent
  - Compressor and/or tank can be located far from actuator cylinder
  - High power per weight at actuator
  - Non-electric, non-magnetic
  - Cheap and simple



#### Actuation - Fluids

## • Pneumatics







## **Actuation - Pneumatics**



Video: Kokoro LTD



- Hydraulics
  - Very powerful per mass
  - Good for static loads
  - Dirty
  - Slow
  - Challenging to control











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Up to 3 kN per cm<sup>2</sup> in actual systems



Applicable torque depends on the configuration

 $\tau = F \times r$ 





Applicable torque depends on the configuration

 $\tau = F \times r$ 





Applicable torque depends on the configuration

 $\tau = F \times r$ 





## Actuation

Characteristics	Pneumatic	Hydraulic	Electric
Complexity	Simple	Medium	Medium/High
Peak power	High	Very high	High
Size	Low size/force	Very low size/force	Medium size/force
Control	Simple valves	Simple valves	Electronic controller
Position accuracy	Good	Good	Better
Speed	Fast	Slow	Fast
Purchase cost	Low	High	High
Operating cost	Medium	High	Low
Maintenance cost	Low	High	Low
Utilities	Compressor/power/ pipes	Pump/power/ pipes	Power only
Efficiency	Low	Low	High
Reliability	Excellent	Good	Good
Maintenance	Low	Medium	Medium

Table 1A: Linear Power Transmission Comparison



- Actuation
  - artificial muscle
  - passive actuation (only braking)



#### Actuation - others

- Artificial muscles
  - piezo
  - pneumatic



Image: Kengoro





## Antagonistic actuators





#### Antagonistic actuators





#### Steering by braking





Thomas Hellström, *An intelligent rollator with steering by braking*, Department of Computing Science Umeå University



## Sensing

- Proprioceptive sensing
  - Pose
  - Force/torque
  - Effort, Voltage, Current
  - Tactile
  - Temperature



- Encoders
  - Sense joint position/angle



- Potentiometer
  - Resistance is function of position







## Potentiometer





• Optical encoders





- Optical encoders
- Incremental patterns
- Needs resetting to determine zero position





- Optical encoders
- Absolute position patterns
- Needs resetting to determine zero position





- Optical encoders
- Absolute position patterns
- Needs resetting to determine zero position





- Hall effect sensors
- Needs resetting to determine zero position
- Uses Hall effect
   The difference in magnetic
   field strength causes
   voltage differences in
   the sensor





• Strain gauge





- Load cell
- Contains flexible metal parts with strain gauges attached
- Linear transformation between measured deformation and applied forces and torques







#### Force and Torque

• Optoforce







- Placement of sensors
  - Sensors at joints gives us the actual torque at each joint, which enables advanced feedback control for arm dynamics
  - Sensors at end effector gives us interaction forces and torques, which enables advanced feedback control for the task
  - End effector forces/torques are related to joint torques by Jacobian

$$au = J^T \mathcal{F}$$







#### Sensing

- Tactile
  - Sense (distribution of) contact forces from the environment
  - Ideally, integral of taxels should give normal force...







# • Tactile sensing for higher frequencies



## Syntouch BioTac



- Sensorless sensing
  - We know that

 $\tau = M(\Theta) \ddot{\Theta} + V(\Theta, \dot{\Theta}) + G(\Theta) + J^{T} F$ 

- If we know the current flowing through the motors, and the torque each motor produces at a given current, we can solve for F
- Sensitive to modelling errors