Light-weight robots

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Light-weight robots are robots especially designed for mobility and interaction with a priori unknown environments and with humans. These applications pose the requirements of a light-weight design with high load to weight ratio and high motion velocity (close to the approximately 1:1 ratio of human arms at a tip velocity of 6m/s). Further, they require a modular, integrated mechanical and electronics design as well as sensing and control capabilities enabling skilful, compliant interaction (*soft robotics*).

Figure 1: Light-weigt robot arm and hand (DLR).

Contents

General description

Typical application areas for light-weight robots are:

- *Service robotics*, including
    - Industrial servicing with a production assistant robot, i.e. a robot which works in the vicinity and possibly in direct cooperation with humans. Such robots are aimed at assisting humans in tasks which were not accessible to industrial robots so far (e.g. assembly, mobile manipulation).
    - Domestic and public servicing, leading to robots which would help humans at home, in hospitals, shops, etc. A huge market is predicted for these applications [Dario et al. 1999].
- *Space robotics*, posing high requirements regarding mobility and autonomy. For such applications, light-weight robots are particularly relevant because of the high costs related to the transportation of heavy masses to space [Hirzinger et al.2001].
- *Medical robotics*. In this field light-weight robots can help the surgeon improving the precision of a surgical operation by directly using digital patient data (CT-scan, MRI, etc.).
- *Force feedback devices* for tele-presence and virtual reality.

The design concept of light-weight robots is contrasting to the design of today’s industrial robots, which are mainly used for repetitive positioning tasks in well structured and a priori determined environments. In order to obtain high positioning accuracy and repeatability, industrial robotic arms are very stiff and implicitly heavy manipulators. They can achieve their tasks using only relatively simple and cost-effective position feedback control. On the other hand, a light-weight design is required in order to permit mobility at low power consumption and ensure the safety of humans in case of robot failure. Moreover, since the position of the robot as well as of the surrounding objects is not known very precisely, such robots cannot rely on high positioning accuracy only. More useful in such environments is a compliant behaviour, by which the arm can accommodate for the uncertainties and limit the interaction forces even in case of imprecise information about the environment. In order to obtain the mentioned compliant behaviour, the external interaction forces and torques have to be measured and fed back to the controller in addition to the position of the joints (see section "Control of Light-Weight Robots").

Therefore, **torque controlled light-weight robots** are the ideal candidates for the application areas mentioned above.

Design approach

Generally, two major design approaches for light-weight robots can be recognized today, a *modular mechatronic approach* and a *tendon actuation approach*. Common to both approaches are

- Light-weight structures. Light–weight metals or composite materials are used for the robot links. Moreover, the design of the entire system (controllers, power supply) is optimized for weight reduction in order to enable the mobile application of the systems.
- Low power consumption due to small moved inertias. Low power consumption is revevant both for safety reasons (new robot standards define robots having less than 80W mechanical power as safe), as well as from point of view of mobility efficiency (influencing the weight of batteries or the area of solar panels).
- Intrinsic compliance of the transmission system. In order to increase performance and/or safety of the arms, in some prototypes, additional (possibly variable) mechanical compliance is introduced into the joints.

For the *modular mechatronic approach* following aspects are of particular interest for obtaining the desired light-weight and performance properties

- Integration of electronics into the joint structure, leading to a modular joint design. This allows the design of robots of increasing kinematic complexity based on the modular joints as in the case of the DLR humanoid Justin. Moreover, one obtains a self-contained system, well suited for autonomous, mobile applications.
- Efficient motors. In contrast to industrial robots, not high velocity motors, but motors with high torque at moderate speed, low energy loss and fast dynamic response are of interest. Special motors, such as the DLR-Robodrive, have been designed for these application.
- Gearing with high load/weight ratio. HarmonicDrive gears are most commonly used.
- Full state measurement in the joints. As will be outlined in the control section, some advanced robots use torque sensing in addition to the position sensing, in order to implement compliant behaviour and a smooth, vibration-free motion.
- Sensor redundancy for safety (e.g, for position, forces, torques, and current sensing)

For *tendon actuated* light-weight robots, there are following specific design principles [Townsend et al.1988],[Townsend et al.1989]

- The actuators are placed in the base of the robot in order to minimize the weight of moved parts.
- The joints are actuated by cables wired to the joints over a pulley system.
- The reduction ratio is low in order to provide mechanical back-drivability.

Limitations and drawbacks of the light-weight robot design:

- The benefits of light-weight robots are obtained at the price of higher elasticities in the joints and the structure leading to a more complex dynamic behaviour, which requires advanced control techniques in order to obtain accurate, performant motion.
- Due to system complexity, higher requirements for sensors and the high-performance components used, the price of those robots is today higher than the price of typical industrial robots.

Examples of light-weight robots

Below are some remarkable light-weight robot arms which are commercially available:

Barrett arm. Courtesy of Barrett Technology, Inc

Mitsubishi PA10 arm

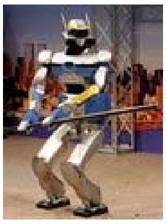
KUKA light-weight arm

- The Barrett arm is a cable driven light-weight arm with the actuators placed at the base of the manipulator, in order to reduce the total moved weight. The joints are back-drivable due to low reduction ratio.
- The Mitsubishi PA10 arm is a commercially available light-weight redundant arm, with a weight of 38kg and a payload of 10kg.
- The KUKA light-weight arm (based on the DLR arm technology)is a redundant robot with seven degrees of freedom, with a weight of 14kg, and a load to weight ratio of 1:1. It has joint torque sensors in each joint and redundant position measurement (on motor and link side)[Hirzinger et al.2000],[Hirzinger et al.2002]. In addition to the position and velocity interface, it has a torque control interface, enabling high performance soft robotics control.

Applications in humanoid robotics

A light-weight robot design is also required in applications implying mobility, either by mobile wheeled platforms or by full humanoids (robots with bipedal locomotion). Below are some outstanding examples.

Honda's Asimo, one of the most popular humanoids. Courtesy of Honda.



HRP Humanoid Robot Platform build by Kawada Industries.

The NASA Robonaut, designed for teleoperation and exploration in space [Bluethmann et al.2001]. Courtesy of the NASA Johnson Space Center.

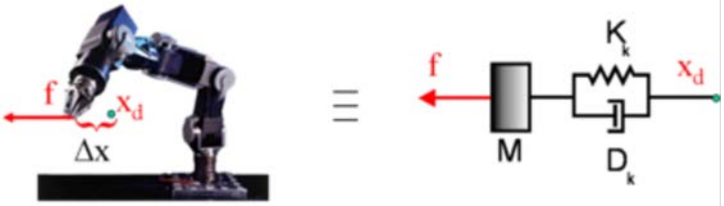
The SARCOS humanoid uses hydraulic actuators with integrated joint torque sensing. Photo supplied by Dr. Stephen C. Jacobsen, President of Sterling Investments LC, Salt Lake City.

The DLR JUSTIN torque controlled humanoid, based on the DLR light-weight robot technology [Ott et al.2006].

Control of light-weight robots

Within the light-weight robot concept, a strong emphasis is set on the design of control laws which can provide robust performance (with respect to positioning and model uncertainty), as well as active safety for the human and the robot during their interaction. Compared to standard industrial robot control, the following aspects are of particular importance:

- Extensive usage of sensor feedback from the environment (including vision, force-torque sensing at the end-effector and in the joints, tactile sensing, distance and proximity sensors).
- Implementation of control laws which do not control only position, but also the interaction forces in the constrained directions. An often used method is "impedance control", where the robot is programmed to act as a virtual mass-spring-damper system with freely assignable parameters. In this way, instead of prescribing a position or a force, the dynamic relation between the two is prescribed, while the actual force and position resulting during interaction depend also on the environment properties Fig.2.
- Position control has to compensate the effects of the inherent robot elasticity (such as vibrations or the steady state position error) to ensure the performance of positioning and trajectory tracking. This problem exists (although in a reduced amount) also for industrial robots moving at high velocities.



$$f = M\Delta\ddot{x} + D_k\Delta\dot{x} + K_k\Delta x$$

Figure 2: Design idea of impedance control

- The robot needs control strategies which allow to detect unexpected collisions with the environment and with humans and to react in a safe manner. Under no circumstances, the robot may constitute a threat to the humans.

Example: the control concepts of the DLR light-weight robot

For the control of the DLR robots, the torque sensors in each joint play a key role [Albu-Schaeffer et al.2007b]. These sensors allow implementing most of the general aspects addressed above with high accuracy and performance.

- An essential feature in the control of the DLR robots is the use of the joint torque sensors for so-called *soft robotics* control, i.e. impedance and force/torque control. One can freely chose the Cartesian impedance (virtual compliance, damping, and mass) and on whatever link one touches the arm, it may react softly, at the same time trying to keep the hand in its pose.
- Collision and failure detection as well as appropriate reaction schemes can be quite sensitive, since the uncertainty of friction forces is eliminated by sensing the torque after the gearbox.

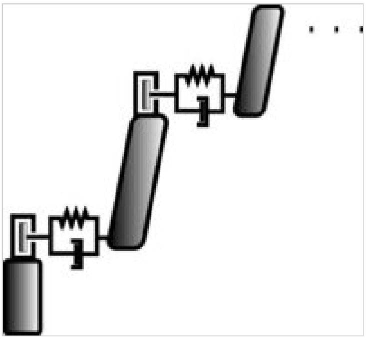


Figure 3: Flexible joint robot

- The torque sensors measure the joint vibration behind the gear-box and therefore enable an active vibration damping. Taking into account the elasticity of the transmission, each joint becomes a mass-spring-damper system (Fig.3.) (and thus a fourth order system), so that the complete state is given by position and velocity (as for the second order rigid robot model), and additionally by the torque and its derivative. Thus, measuring the torque is essential for implementing full state feedback control laws [Albu-Schaeffer et al.2007a].
- Torque feedback allows compensating the frictional effects and letting the actuator act as a high fidelity torque source [Vischer et al.1990]. Therefore, it is possible to realize the kernel of all modern robot control concepts (e.g. Khatib`s operational space approach), namely to prescribe a certain path (defined by acceleration vector $a$ ) of the end-effector and certain forces/torques $f_{\mathrm{exert}}$ to be exerted on the environment. Similar to Newton`s scalar law $f = ma$ (force is mass multiplied by acceleration) one has now to generate a virtual force-torque vector f at the end-effector given by

$$f = Ma + \mathrm{gravity} + (\mathrm{Coriolis,\ centrifugal\ forces}) + f_{\mathrm{exert}}$$

where M is the variable mass matrix of the robot. The corresponding joint torque vector τ which is needed is easily found by the relation

$$\tau = J^T f\,,$$

where J^T is the transpose Jacobion at the actual robot configuration.

- Another feature of using joint torque sensing is the fact that in this design, the sensors are placed close to the actuators, such that the torque control loop has to be closed only over the actuator dynamics, but does not include the nonlinear robot dynamics and the compliance of the entire robot structure.

The close integration of actuators and sensors is advantageous from a control point of view, enabling robust, *passivity based control* approaches. The preference for passivity based control is another consequence of the fact that the mechanical properties of the manipulated objects and of the contacted environment are not known precisely. All controllers have intuitive physical interpretations related to passive mechanical elements, such as virtual inertias or multi-dimensional springs and dampers. Thus, the amount of energy introduced into the system by the controller is directly monitored. Therefore, stability can be ensured in contact with any environment, as long as it displays a passive behaviour as well. The same controller structure is used for position, torque and impedance control and the system can switch within 1ms between the various controllers (Fig.4.).

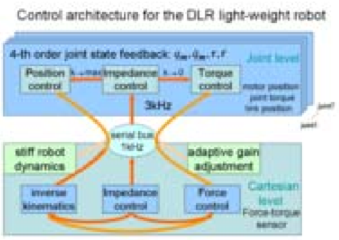


Figure 4: Flexible joint robot

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Recommended reading

- None

External links

- Gerhard Hirzinger's website (http://www.dlr.de/rm-neu/en/desktopdefault.aspx)
- Alin Albu-Schaeffer's website (http://www.robotic.dlr.de/Alin.Albu_Schaeffer/)
- Barrett Technology, Inc. (http://www.barrett.com/robot/index.htm)
- KUKA Robot Group (http://www.kuka.com/en/pressevents/news/NN_060515_Automatica_02.htm)
- Honda's Asimo webpage (http://asimo.honda.com/)
- HRP Robots webpage (http://www.plyojump.com/hrp.html)
- NASA Robotnaut Program (http://robonaut.jsc.nasa.gov/)
- SARCOS webpage (http://www.sarcos.com)
- Justin at DLR's webpage (German) (http://www.dlr.de/desktopdefault.aspx/tabid-667/1157_read-8766/)

See also

Human-robot interaction, Robot kinematics, Robotics

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