FONDAZIONE ISTITUTO ITALIANO DI TECNOLOGIA

A TECHNOLOGY TEASER

ACTUATORS FOR ROBOTIC APPLICATIONS

Released on May 2016

ROBOTICS

Istituto Italiano di Tecnologia – Mission and History

The Foundation is intended to promote Italy's technological development and advanced education, consistent with national policies for scientific and technological development, thus strengthening the national production system.
For this purpose, the Foundation:
- helps and accelerates the development, within the national research system, of scientific and technological skills able to facilitate state of the art technological advancements of the national production system;
- develops innovative methods and know-how, in order to facilitate new high-level practices and positive competitive mechanisms in the field of national research;
- promotes and develops scientific and technological excellence, both directly, through its multi-disciplinary research laboratories, and indirectly, through a wide collaboration with national and international laboratories and research teams;
- carries out advanced training programs as a part of wider multi-disciplinary projects and programs;
- fosters a culture based on sharing and valuing results, to be used in order to improve production and for welfare-related purposes, both internally and in relation to the entire national research system;
- creates technological understanding about components, methods, processes and techniques to be used for the implementation and interconnection of innovative products and services, in strategic areas for the competitiveness of the national production system;
- pools research scientists operating in various research institutes and establishes cooperation agreements with high-level, specialized centers;
- promotes interactions between basic research and applied research facilities, encouraging experimental development;
- spreads transparent, merit-based selection mechanisms for research scientists and projects, in compliance with globally approved and established criteria.

CONTENTS

EXECUTIVE SUMMARY

Industrial robotic applications are already well known and more and more common in manufacturing companies, where automation and the possibility to cut costs have led the progress so far.
Although the possibility to substitute humans for robots on a production line will always be appealing, in the future it won't grant the same competitive advantages as today, since there will be less and less room for automation.
For this reason, robotics is expected to reach a new different level in the future. As a matter of fact, robotics certainly has the potential to bring disruptive innovations in next years and not only in industrial environment.
However, a robot moving out of a company, maybe at home or in a hospital, which is not supposed to substitute humans, but has to collaborate and interact with them, requires a different technology from the one currently in use.

Robotics, and in particular human/legged robotics, is one of the core research programs in IIT. Human/legged robots represent a challenge from different point of views, above all the inter-disciplinary approach which is necessary to deal with them.
The studies in this sector have led to a solid knowledge in robotics and a notable amount of patented technologies, of which rotary and linear actuators are just an example. These actuators having elastic elements and/or variable properties aim to reach new behaviors and performances and represent a first but necessary step towards the collaboration between humans and robots.

These technologies represent a unique chance for companies active in robotics field and willing to branch out into different market areas.

INTELLECTUAL PROPERTY

IIT Technology Transfer is ensuring proper protection of the technology. Details on the PCT filed patent applications and granted patents are following.

PCT International Application #
PCT/IB2010/050310 – 19th August 2010
Priority Application #
TO2009A000042 – 23rd January 2009
Applicant
Fondazione Istituto Italiano di Tecnologia
Inventors
Jody Saglia, Nikolaos Tsagarakis, Jian Dai, Darwin Caldwell
Title
Linear actuator and rehabilitation device incorporating such actuator

The technology has been granted the European Patent EP 2381910 on 22nd August 2012, the US Patent US 8986232 on 24th March 2015 and the Chinese Patent ZL201080013428.X on 25st June 2014.

PCT International Application #
PCT/IB2011/051877 – 28th April 2011
Priority Application #
TO2010A000360 – 28th April 2010
Applicant
Fondazione Istituto Italiano di Tecnologia
Inventors
Matteo Laffranchi, Nikolaos Tsagarakis, Darwin Caldwell
Title
Elastic Rotary Actuator, Particularly For Robotic Applications, Provided With A Damping Device

The technology has been granted the European Patent EP 2564085 on 17th September 2014 and the US Patent US 8727894 on 20th May 2014.

PCT International Application #
PCT/IB2013/056834 – 23rd August 2013
Priority Application #
TO2012A000743 – 28th August 2012
Applicant
Fondazione Istituto Italiano di Tecnologia
Inventors
Francesco Nori, Bastien Berret, Luca Fiorio, Alberto Parmiggiani, Giulio Sandini
Title
Variable-Stiffness Actuator With Passive Disturbance Rejection

The PCT has been nationalized in Europe. The European Application EP 13785613.4 is still pending.

Priority Application #
TO2009A000257 – 3rd April 2009
Applicant
Fondazione Istituto Italiano di Tecnologia
Inventors
Nikolaos Tsagarakis, Darwin Caldwell, Matteo Laffranchi, Bram Vanderborght
Title
Elastic rotary actuator, particularly for robotic applications, and method for controlling the same

The technology has been granted the US Patent US 8569988 on 29th October 2013. The European Application EP 10158648.5 is still pending.

Priority Application #
TO2011A000848 – 23rd September 2011
Applicant
Fondazione Istituto Italiano di Tecnologia
Inventors
Ivar Thorson, Gianluca Pane
Title
Elastic Rotary Actuator

The technology has been granted the Italian Patent IT 0001407702 on 30th April 2014 and the US Patent US 8821338 on 2nd September 2014.

IIT TECHNOLOGY

Actuators are essential devices in Robotics and widely common, particularly for industrial applications. However, humanoid/legged robots have different needs than industrial robots; in order to meet these different needs, IIT researchers have developed new types of actuators. Initially conceived for humanoid robotics, they may have positive side effects also in Industrial robotics, thanks to their unique properties.

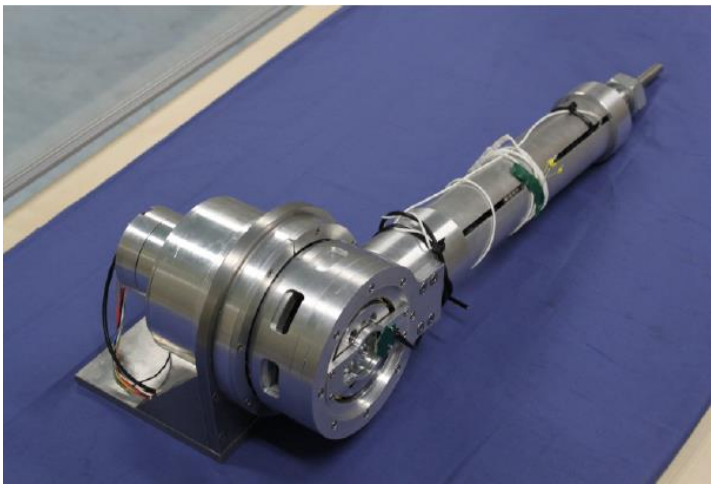
Five actuators (4 rotary and 1 linear) developed and patented by IIT are briefly described below.

Elastic Rotary Actuator (Priority App. TO2011A000848)

Actuators have generally the possibility to control speed and position. The future of robotics will rely heavily on actuators with force/torque control. For example, control on force/torque is necessary for manipulating fragile items, as humans can do.

Electric actuators are suitable for this purpose, yet not optimized. As a matter of fact, robotic arms and legs should reproduce the ability of human arms and legs on several levels. However, human muscles in limbs can also store energy and have a sort of internal elasticity. In order to reproduce this behavior, one or more elastic elements are inserted in electric actuators.

The actuator described in this paragraph is a type of elastic rotary actuator.



It has three main parts:

(1) A low-reduction compound planetary gear reduction unit;

(2) A hypocycloid mechanism used for stretching a spring;

(3) A differential unit that connects (1) and (2) with a 2:1 reduction ratio.

An electric motor creates the rotational movement; the hypocycloid mechanism converts the rotation in translation in the direction of the spring.

The actuator uses essentially two sensors during normal operation: one relative position encoder which measures the rotor position, and a second encoder to measure the deflection of the spring from the equilibrium position. These provide clean and robust information for use in precise force control. During calibration, a load cell which measures the tension in the spring is also used to help adjust the tension to the desired amount.

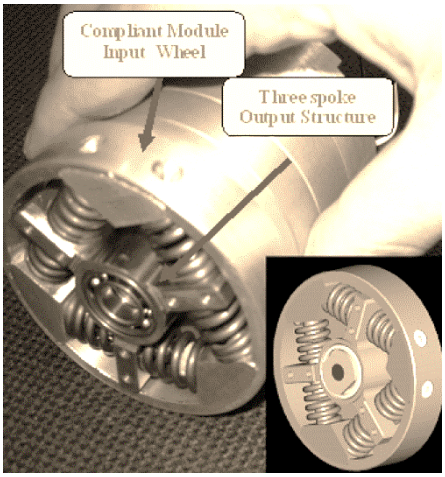
The invention is optimized to be highly effective for mobile robots with legged locomotion, as that is an eye-catching demonstration of actuation technology. However, the invention is not limited to legged locomotion tasks. Minor variations on the relative sizes of each component and further miniaturization would make the invention highly desirable to researchers in torque control, grasping/manipulation, mobile robotics, high-speed dynamic robots, safe human-robot interaction tasks, and soft-contact industrial manufacturing tasks currently performed by humans.

Elastic rotary actuator, particularly for robotic applications, and method for controlling the same (Priority App. TO2009A000257)

Soft robotics is a new field in robotics; the idea is to make all of the components in the robot soft and flexible in order to move in very limited spaces and change gaits fairly easily.

Previous implementations of soft actuators are not modular, exhibit high mechanical complexity and their size, weight, cost prevent their widespread. As a result, their application to multi degree of freedom robotic machines still remains an open issue and challenging task.

On the contrary, the elastic rotary actuator described below has a very compact design and, as a consequence, a limited weight.

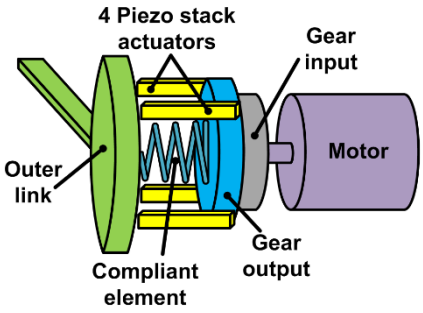


The actuator is composed by a motor, a reduction drive and a compliant module; the compliant module has six linear springs which are arranged in a particular layout (see picture on the right). Two absolute position sensors have been integrated within the actuation group measuring respectively the mechanical angle of the motor after the reduction drive and the deflection angle of the compliant module. The two sensors not only allow the monitoring of the link position but also allow the evaluation of the joint torque.

Thanks to this unique design, it possible to regulate the stiffness of the springs: the patent application is provided with the dynamic equations.

Elastic Rotary Actuator, particularly for robotics application, provided with a damping device (Priority App. TO2010A000360)

This actuator is a variant of the previous one. Adding one or more elastic elements in an actuator may lead to the need for damping in order to reduce undesired oscillations. Four piezoelectric units are inserted around the compliant module; this solution allows to modulate the damping properties, to keep a compact design and requires a small amount of power.

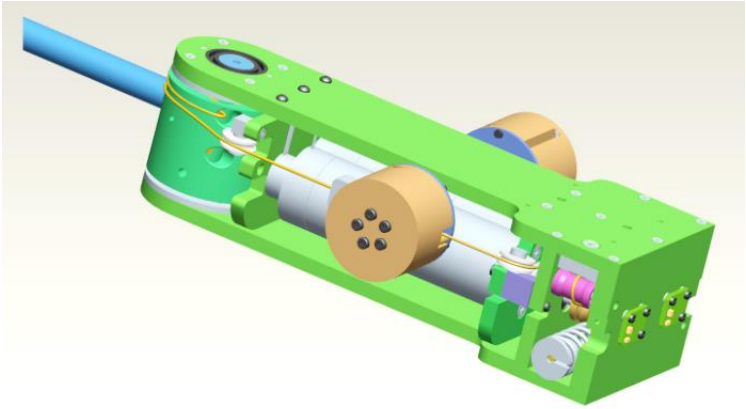


Variable stiffness actuator with passive disturbance rejection (Priority App. TO2012A0000743)

This actuator has the fundamental ability to increase passive disturbance rejection. In this context, the adjective “passive” refers to the fact that rejection is not obtained with active control loops but derives from the intrinsic (passive) properties of the system.

The proposed design is based on an agonist-antagonist configuration of two electric motors. The insipiration for this design comes from the human muscle co-activation; in fact, recent interpretations of this phenomenon suggests that muscle co-activation augments the limb passive disturbance rejection.

This actuator has two motors, two reduction units and several elastic elements which facilitate the control on force and torque.



A group of cables, pulleys and spools convert the rotational displacement of the motors in linear displacement to the elastic elements; then the linear displacement of the elastic elements is converted in angular displacement to the output element.
The control on force/torque is performed through different position sensors which measure angular position; stiffness regulation is obtained by non-linear springs and not-circular spools.

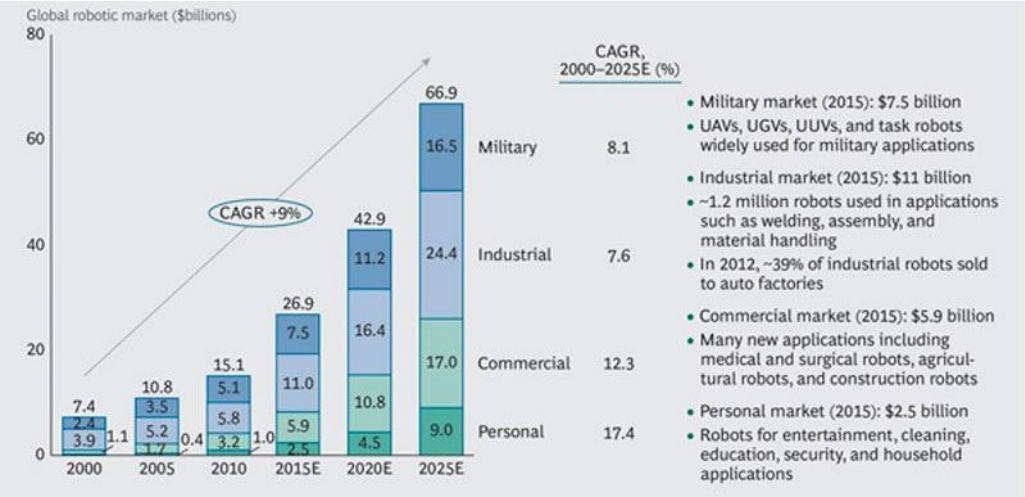
Linear actuator and rehabilitation device incorporating such actuator (Priority App. TO2009A000042)

This actuator is linear; it has one motor which creates angular displacement; through a conversion unit composed by cables and pulleys, the angular displacement becomes linear displacement for the output element. The patent application covers different designs and solutions to reach the goal.
The actuator is equipped with full state sensing, namely an encoder for position and velocity measurements and an axial load cell mounted on the tip of the moving piston. This allows to control the actuator in either position/velocity or force.
A combination of three actuators has become part of a rehabilitation device for the ankle. This device can accelerate and significantly improve the functional recovery of patients with ankle impairments. The simplicity and compactness of the device together with its redundant characteristic, which allows simultaneous control of position and stiffness, improves the quality of and increase the productivity of ankle physiotherapy delivered by the clinicians.

MARKET ANALYSIS

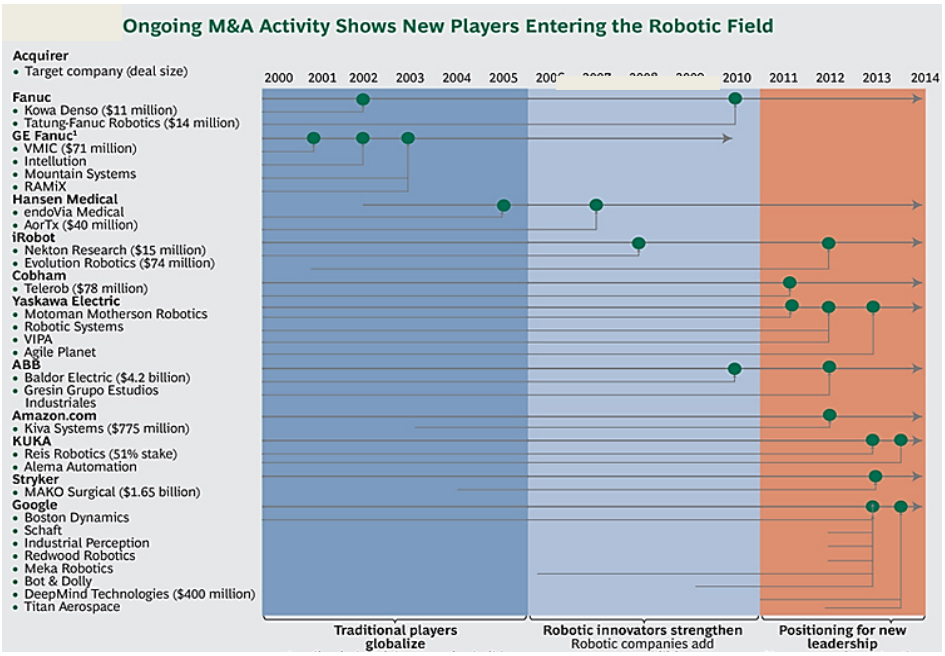
Robotics Market

The actuators described previously can be framed up in the Robotics market. This market is expected to increase at a sustained **9% CAGR** (*Compound Annual Growth Rate*) in next ten years, reaching **67 Billion** by 2025 (Sources: International Federation of Robotics, Japan Robot Association, BCG analysis)



Although all areas are promising, the highest growth rate are expected in Commercial and Personal markets. In last years robots have spread widely in the industrial market, especially in automotive sectors: historically, robots were used in manufacturing largely for repetitive tasks that require speed, strength, and moderate precision, such as material handling and processing, welding and soldering, and assembly. Nowadays robots applications are increasing in every area, even in nonindustrial enviroments: mining robots, warehouse robots, caregiver robots and agricultural robots are just few examples.

Besides, mainly in last five years, important players in this market are trying to consolidate their position through mergers and acquisitions, while also nonrobotic companies, such as Google and Amazon, are supporting huge investments and are expected to become leading companies in these areas as well. (Sources: S&P Capital IQ, BCG analysis)

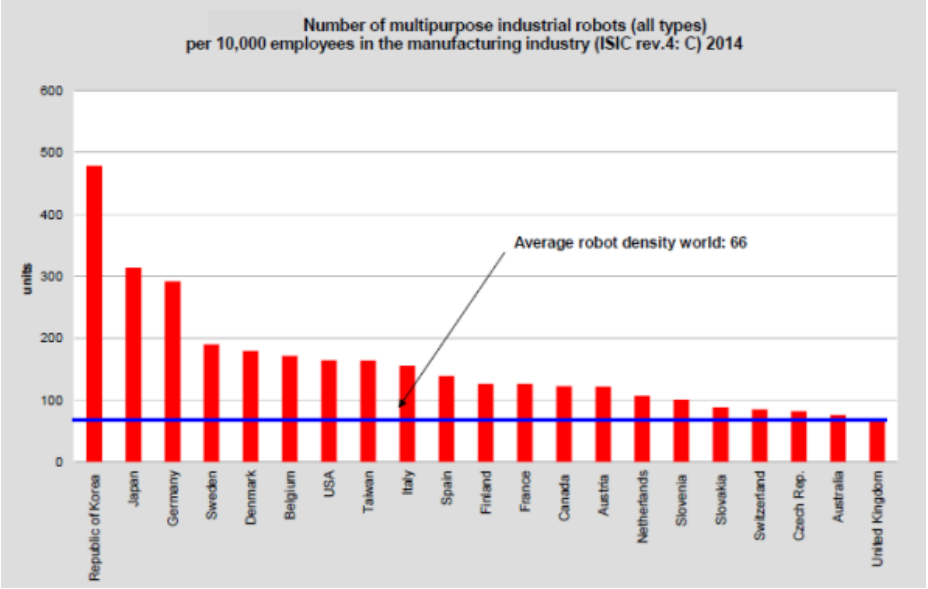


However Robotics market is focused in some regions of the world. The table below reports the industrial robotic units sold in 2014:

Industrial Robotics: market demand

Country	Sales	2013 >> 2014
China	57.096	+56%
Japan	29.300	+17%
United States	26.200	+11%
Rep. of Korea	24.700	+16%
Germany	20.100	+10%
Taiwan	6.900	+27%
Italy	6.200	+32%

The first five countries represent 70% of total market. The figures are important considering that some of these countries have already a high *robot density*, as suggested in the picture below.



The robot density (number of robot per 10.000 employees) is a parameter which gives an approximation of the level of automation in the manifacturing industry. Despite being already high in Korea, Japan and Germany, there is still a sustained positive trend in robotic units sold.

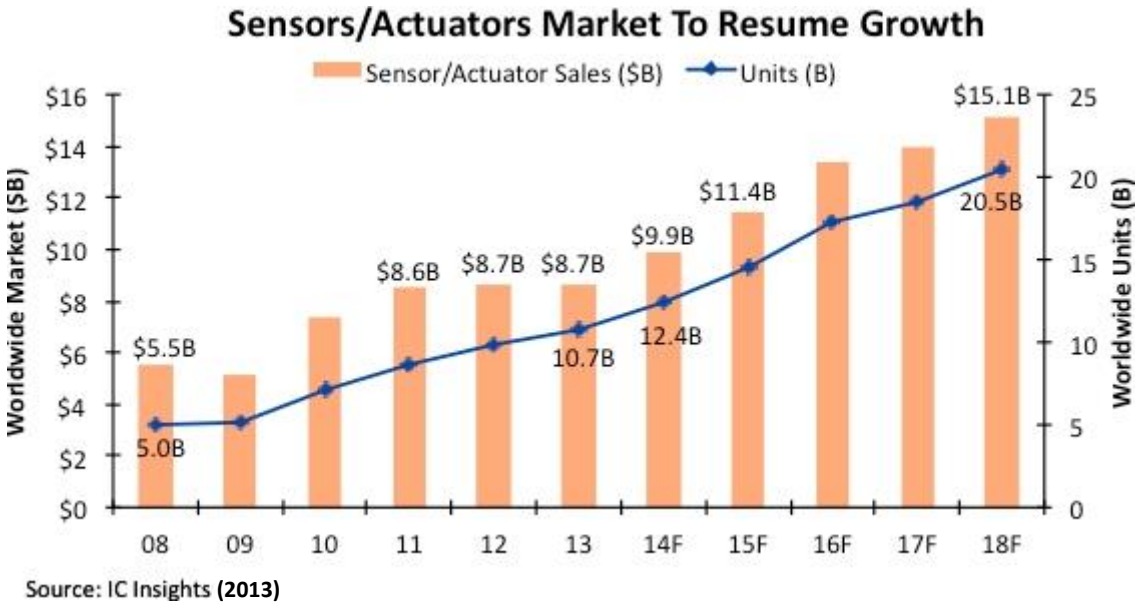
Actuators Market

The market of actuators for robotics application is obviously correlated to the more generic Robotics market. In fact, actuation systems are an enabling technology for robotics application. Fast, safe, low-cost, and reliable robots are necessary for many mobile robots and human-robot interaction applications. This requires new actuators and transmissions that have high torque-to-weight, power-to-weight, are safe interacting with people, are robust to impact, have appropriate impedance for interactive tasks, and have reasonable speed and efficiency.

The following segments of the world robot market are expected to grow rapidly if necessary actuator technologies are developed.

- *Physical assistance of humans by robots*, such as carrying a person upstairs, requires light weight actuation with appropriate impedance
- *Micro mobile sensor nodes for security* requires miniature high performance actuators, such as for microflight
- *Power suits and prosthetics* require high power, high torque, high efficiency actuators
- *Domestic robots* require safe, low cost, low inertia actuators for mobility plus manipulation

In the picture below the growing trend of actuators (and sensors) market is visible.



Source: IC Insights **(2013)**

For example, in 2014 actuators Italian market was estimated to make up 410-420 million €; 90% of the revenues came from export activities. Pneumatic actuators constituted 60% of the total sales, while electric and hydraulic actuators composed remaining 40%.

Rotary Actuators Focus

Finally, the rotary actuators market is a subset of the wider actuators market. In the past, the main issue about automation was to create robots capable of repeating the same movements as humans, with no disturbs and greater precision. The possibility to substitute people has been one of the main driver in automation technology development so far.

Nowadays, new needs are arising. First of all, robotics applications are moving from Industrial market to other fields, where the work environment is unmapped and dynamic. New types of robots will most likely act as coworkers that help humans — and assemble devices on manufacturing lines, for example. Others strap onto human limbs to make soldiers stronger or paraplegics mobile. Still others navigate households or outdoor environments and must move themselves efficiently.

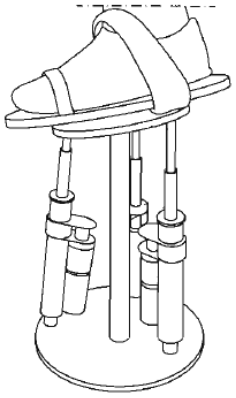
In order to reach the scope, new actuators, especially rotary ones, have to be adopted. For example, more sophisticated forms of controls will avoid the risk for the robots to hurt nearby humans while moving.

Since no numeric data is available about sales of rotary actuators in the world, in this section only a list of potential application for these actuators will be reported:

- Research institutes: Legged Robots, Humanoid robots, automation research…
- Manufacturing industries: Production process, Packaging, Logistics…
- Domestic: Housecleaning, assistance, gardening and agriculture…
- HealthCare & Assistance structures: Hospitals, Long-care assistance, nurse houses…
- Other: Education, entertainment, security…

Rotary actuators are necessary for every robotics application in which a rotational movement is necessary, for example in legged robots. Besides, elastic actuators make the robots eligible to work near humans or delicate goods: the control on torque is a necessary feature for this scope.

Linear Actuators focus



The above considerations for rotary actuators are valid for linear actuators as well: branching out to new markets will necessarily require an upgrade of existing technology. Especially in medical environment these actuators may have several applications: rehabilitation devices (see picture), prosthesis and exoskeletons are just few examples.

In rehabilitation, robotic aids can impact and increase the healthcare quality and resources productivity introducing new efficiency into certain routine physical and occupational therapy activities.

In these cases, it is evident once again that robots will not substitute humans, but will support them in their life, in a broader sense. For this reason, linear actuators will have to meet new needs: compactness, elasticity, variable stiffness or damping are recurring concepts in this family of actuators.

In general, linear actuators, as well as rotary ones, will allow to enable a new level of interaction between humans and robots.

Main sources

https://www.bcgperspectives.com/content/articles/business_unit_strategy_innovation_rise_of_robotics/
https://christophegazeau.wordpress.com/2014/12/
http://www.ifr.org/industrial-robots/statistics/
http://www.technavio.com/blog/top-21-companies-in-the-industrial-robotics-market
http://www.ifr.org/service-robots/statistics/
http://www.us-robotics.us/reports/CCC-ETT_9.pdf
http://machinedesign.com/robotics/rise-soft-robots-and-actuators-drive-them
http://automazione-plus.it/wp-content/uploads/sites/3/2014/12/AS_09_18-19.pdf

COMPETITIVE SCENARIO

Rotary actuators

A great variety of rotary actuators is available on the market. As a consequence, rotary actuators can have very different performances. An ideal rotary actuator should have the following properties:

- High maximum torque
- High maximum angular speed
- High power/weight ratio
- High energy performance
- High force generation bandwidth
- Low mechanical impedance in the event of position disturbances

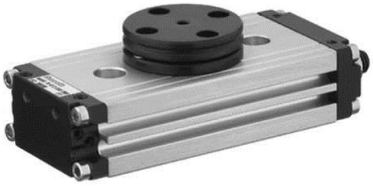
Below a short recap of the performances of the existing technologies is reported.

1) Hydraulic rotary actuators

These actuators have excellent maximum torque, angular speed and power/weigh ratio, but a very high mechanical impedance.

2) Pneumatic rotary actuators

These actuators have an intrinsic compliance because they contain a compressible gas, but they are affected by band control problems because of the limits of their valves in terms of flow rate and tightness.



3) Electric rotary actuators

These actuators are fast, but generate low torques. They have to be integrated with one or more reduction units, with the consequence of increasing frictions and mechanical impedance.

None of these basic solutions guarantees the best performances. However, electric rotary actuators can be improved adding an elastic element, such as a metal spring. If there's a disturb in the position of the external load, the force in the spring slowly increases: this is a good behavior against impulsive load and allows to improve the control on force and torque. For this reason, these actuators are becoming more and more popular for robotics applications.

Priority Application TO2011A000848: strengths

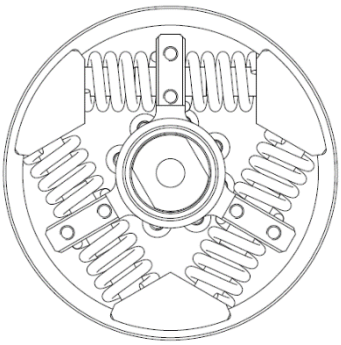
The elastic rotary actuators described in this document want to propose a solution for the issues of available actuators in the market.
The actuator with the hypocycloid mechanism has the following advantages:

a) The mechanism produces a non-linear deformation of the elastic means due to the combination of the hypocycloid mechanism and the planetary reduction: this allows to reduce mechanical inertia.
b) The spring can store energy independently of the direction of the rotations, granting a symmetrical behavior.
c) Better control in force and torque, due to the angular position sensor which measures directly the deflection angle.
d) The spring can store a good amount of energy.

Although it is designed for humanoid robots, the actuator can be easily modified to be adopted in other fields of robotics.

Priority Application TO2009A000257: strengths

The main advantages of this actuator are the following ones:

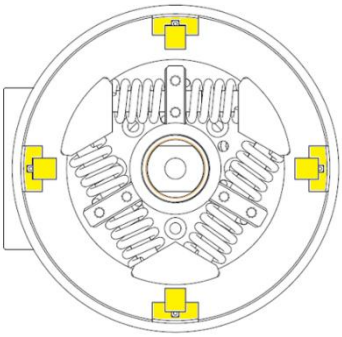


a) It's a very compact solution
b) It has a high level of modularity, making it suitable for robotic applications.
c) The stiffness is variable and can be controlled

The actuator below can be considered a variant of this one.

Priority Application TO2010A000360: strengths

Adding an elastic element in the actuator may result in an oscillation around the desired position or rotation. For some applications this behavior is not acceptable. This actuator can prevent this behavior. The major benefits are the following ones:



a) A damper which can be regulated
b) Piezoelectric actuation (highlighted in the picture): this technology allows to maintain a compact actuator and reduce the use of energy
c) The compactness, the wide possibility of controls over variables and the number of degrees of freedom make this actuator extremely suitable for robotic applications.

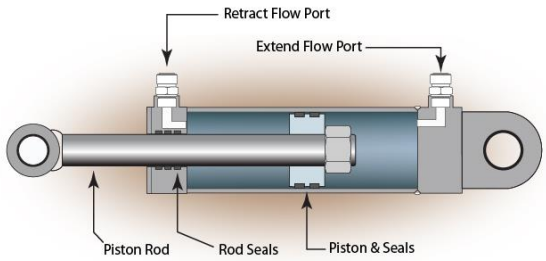
Priority Application TO2012A000743: strengths

This actuator has variable stiffness as well. However, it has also the following peculiarity: it can increase passive disturbance rejection. This ability derives from intrinsic (i.e. passive) properties of the system. As a consequence, there is no need for a control loop.
The proposed design is based on an agonist-antagonist configuration of two electric motors. Stiffness regulation is obtained by non-linear springs, which can be stiffened up via motors co-activation.
The actuator is suitable to all applications that include outside operation, unknown scenarios, human-robot cooperation and intrinsically dynamical instable tasks. Furthermore, the principle behind the new actuator can be applied to construct low cost prototypes and small modular components.

Linear actuators

Linear actuators can have very different performances. For Robotic applications, especially in non-industrial environment, the following features are generally required:

- High speed and force output
- Backdrivability
- High power/weight ratio
- High power/size ratio
- Long stroke and high position resolution
- Possibility to control position, speed and force



Linear actuators are generally hydraulic or pneumatic. Actually fluids can generate very high forces and high speed. For these reasons, hydraulic and pneumatic actuators are widely in use in industrial environment.
Electro-mechanical linear actuators have an electric motor which generates rotary motion. Then the rotary motion is converted to linear displacement. These actuators have different advantages: limited maintenance needs and a better energy efficiency, for example.

Priority Application TO2009A000042: strengths

The linear actuator described in this document is electro-mechanical. In addition to the features of electro-mechanical actuators, it has some distinct properties, which make it competitive and suitable for robotics application.

- High speed and force output, despite the compactness: the actuator has very low friction and apparent inertia.
- As a consequence, it is possible to obtain very high power compared to size and weight.
- Through a gearbox having reduction ratio lower than 20:1, the gearing friction is low and the motor can be easily backdriven.
- The actuator can elongate up to almost double its length and has a very high position resolution given by the motor mounted optical encoder. The other sensors allow to control the actuator also in speed and force.

Key players and major companies

Main companies in Industrial Robotics market in the world:

- ABB (Switzerland, http://www.abb.com/)
- Fanuc (Japan, http://www.fanuc.eu/it/it/robot)
- Yaskawa Motoman (USA, http://www.motoman.com/index.php)
- Adept Technology (USA, http://www.adept.com/)
- Apex Automation & Robotics (Australia, http://www.apexautomation.com.au/)
- Aurotek Corp (Taiwan, http://www.robot.com.tw/EN/)
- Axium Inc. (Canada, http://www.axiumsolutions.com/)
- Daihen Corp. (Japan, http://www.daihen.co.jp/english.html)
- Denso Wave Inc. (Japan, http://www.denso-wave.com/en/)
- Ellison Technologies Inc. (USA, http://www.ellisontechnologies.com/)
- Kawasaki Robotics Inc. (Japan, https://robotics.kawasaki.com/en1/)
- Kuka AG (Germany, http://www.kuka-ag.de/en/)
- Mitsubishi Robotics Corp. (Japan, http://mitsubishirobotics.com/)
- Nachi Fujikoshi Corp. (Japan, http://www.nachi-fujikoshi.co.jp/eng/)
- Pari Robotics (India, http://www.parirobotics.com/)
- Reis Robotics (Germany, http://www.reisrobotics.de/en/home)
- Rockwell Automation Inc. (USA, http://www.rockwellautomation.com/)
- Schunk GmbH (Germany, http://www.schunk.com/)
- Staubli International AG (Switzerland, http://www.staubli.com/en)
- TM Robotics (UK, http://tmrobotics.co.uk/)
- Yamaha Robotics (USA, https://www.yamaharobotics.com/)

List of companies in Humanoid/Legged Robots market in the world:

- Kondo Kagaku Co. (Japan, http://kondo-robot.com/)
- Vstone Co. (Japan, http://www.vstone.co.jp/english/)
- Engineered Arts Limited (UK, https://www.engineeredarts.co.uk/)
- Aldebaran Robotics (France, https://www.aldebaran.com/en)
- Boston Dynamics (USA, http://www.bostondynamics.com/)
- KAWADA Robotics (JP, https://www.kawadarobot.co.jp/index_en.html)
- Robotis (South Korea, http://en.robotis.com/index/)
- Rethink Robotics (USA, http://www.rethinkrobotics.com/)
- Toyota (Japan, http://www.toyota-global.com/innovation/partner_robot/)
- Agility Robotics (USA, http://www.agilityrobotics.com/)
- Honda Robotics (Japan, http://world.honda.com/HondaRobotics/)

List of companies in Actuators market in the world:

- MOOG (USA, http://www.moog.com/)
- Yahama (Japan, http://global.yamaha-motor.com/business/robot/)
- Kinova Robotics (Canada, http://www.kinovarobotics.com/)
- Intelligente Actuator (IAI) (USA, http://www.intelligentactuator.com/)

- LC Automation (UK, https://www.lcautomation.com/)
- PHD (USA, https://www.phdinc.com/)
- Dewert (Germany, http://www.dewert.de/welcome-to-dewert/)
- Thomson Lineaer (USA, http://www.thomsonlinear.com/website/com/eng/index.php)

List of companies in Industrial Robotics market in Italy:

- Italiana Robot, http://www.italianarobot.com/
- ARS Automation, http://www.arsautomation.com/automazione-flessibile/robot-industriali/
- Universal Robot, http://www.universal-robots.com/it/
- Robotecnica, http://www.robotecnica.it/
- ABL Automazione, http://www.ablautomazione.com/
- Arroweld, http://www.arroweld.it/
- B.A.I Automazione, http://www.baiautomazione.it/
- DUEPi, http://www.duepiautomazioni.it/it/
- FlexLink Systems, http://www.flexlink.com/it/
- Heidenhain Italiana, http://www.heidenhain.it/
- Roboteco, http://www.roboteco.it/
- Tiesse Robot, http://www.tiesserobot.it/

List of companies in Actuators market in Italy:

- UmbraGroup, http://www.umbragroup.it/
- Linak, http://www.linak.it/
- Gruppo AUMA, http://www1.auma.com/cms/AUMA/italy/
- Maxon Motor, http://www.maxonmotor.it/
- Servomech, http://www.servomech.it/
- Stabilus, http://www.stabilus.com/it/
- Rollon, http://www.rollon.com/IT/it/

FOR FURTHER READING

- J.A. Saglia, N.G. Tsagarakis, J.S. Dai and D.G. Caldwell
  "*Inverse-kinematics-based control of a redundantly actuated platform for rehabilitation*" (2008)
  PROCEEDINGS- INSTITUTION OF MECHANICAL ENGINEERS PART I JOURNAL OF SYSTEMS AND CONTROL ENGINEERING, Vol. 223, No. I1, 2009, p. 53 - 70.
  DOI: 10.1243/09596518JSCE622

- J.A. Saglia, J.S. Dai and D.G. Caldwell
  "*Geometry and Kinematic Analysis of a Redundantly Actuated Parallel Mechanism That Eliminates Singularities and Improves Dexterity*" (2008)
  Journal of Mechanical Design, Vol. 130, No. 12, 124501, 12.2008, p. 1245011-1245015.
  DOI: 10.1115/1.2988472

- J.A. Saglia, N.G. Tsagarakis, J.S. Dai and D.G. Caldwell
  "*A High Performance 2-dof Over-Actuated Parallel Mechanism for Ankle Rehabilitation*" (2009)
  2009 IEEE International Conference on Robotics and Automation, p. 2080 - 2086.
  DOI: 10.1109/ROBOT.2009.5152604

- N.G. Tsagarakis, M. Laffranchi, J.S. Dai, and D.G. Caldwell
  "*A compact soft actuator unit for small scale human friendly robots*" (2009)
  Robotics and Automation, 2009. ICRA '09. IEEE International Conference on, p.4356 – 4362
  DOI: 10.1109/ROBOT.2009.5152496

- I. Thorson and D.G. Caldwell
  "*A Nonlinear Series Elastic Actuator for Highly Dynamic Motions*" (2011)
  2011 IEEE/RSJ International Conference on Intelligent Robots and Systems, p.390 – 394
  DOI: 10.1109/IROS.2011.6094913

- B. Berret, G. Sandini and F. Nori
  "*Design principles for muscle-like variable impedance actuators with noise rejection property via co-contraction*" (2012)
  2012 12th IEEE-RAS International Conference on Humanoid Robots, p. 222 - 227
  DOI: 10.1109/HUMANOIDS.2012.6651524

- F. Nori, B. Berret, L. Fiorio, A. Parmiggiani and G. Sandini
  "*Control of a Single Degree of Freedom Noise Rejecting - Variable Impedance Actuator*" (2012)
  Robot Control, Volume # 10 | Part# 1, p. 473-478
  DOI: 10.3182/20120905-3-HR-2030.00175

CONTACTS @IIT

Fondazione Istituto Italiano di Tecnologia (IIT)
Via Morego 30 - 16163 Genova, Italy
Tel: +39 010 71781 - Fax: +39 010 720321
C.F. 97329350587 - P.I. 09198791007
Technology Transfer – technology.transfer@iit.it