NOWADAYS TRENDS IN ROBOTICS AND AUTOMATION IN CONSTRUCTION INDUSTRY: TRANSITION FROM HARD TO SOFT ROBOTICS

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Abstract: The actual research trends in robotics and automation in construction industry (RAC) are much different in comparison with the last decade. While during the 90s the R&D activities were focused in the development of new robotic systems (most of them teleoperated) and in existing machinery automation, the actual efforts are concentrated more in the software integration, sensory data acquisition and processing, safety and secure systems, sensor-based process control and construction industrialization. This paper deals with the short state-of-the-art in the actual and features RAC research areas, including representative examples.

Keywords: Automation, hard and soft robotics, civil infrastructures, house building, research trends.

1 INTRODUCTION

The construction industry is one of the most unfamiliar R&D fields in the robotics and automation community. Nevertheless the construction industry is one of the oldest and largest economic sectors. The construction industry's contribution to the GDP in industrialized countries is about 7-10%. In the US this contribution rises to 12% and in the EU there are about 2.7 M enterprises (most of them SME) involving in the business. This data is comparable with manufacturing industry but with double investment in R&D for manufacturing.

During the old ages the technological level of construction industry was very high for their historical period. The old civilizations build very long lasting structures like pyramids, acropolis, aqueducts, cathedrals, etc. They used innovative processes and elements. Nevertheless, nowadays some construction processes change not so much. For example, the building erection process has changed very little over the past eighty years. The middle ages pulleys are substituted by cranes. They are more sophisticated than centuries ago, but work with the same philosophy: manual control, human operator visual feedback, big positioning error, etc. The only elements that have change are: the actuators (electrical motors instead of human force) and materials (steel based instead of wood). These two advances permit to increase the elevation speed, payload and reachability. But construction philosophy is not changed a great deal.

In the field of service robotics the construction industry is one of the most important areas of research. The main difficulty of RAC is related with on-site out-door environment's conditions that are very unstructured. The manipulation of heavy pieces, big tolerances, low level of standardization, medium level of industrialization and pre-fabrication, intervention of numerous non-coordinated actors (architects, builders, suppliers, etc.), etc. are others important features of this sector. This is why all the involved actors (researchers, companies and administrations) must make new efforts to increase the automation level of this important sector.

During the 90s the R&D activities in the field of RAC were leadered by Japanese companies and universities, and were focusing in the development of new robotic systems (most of them teleoperated) and in existing machinery automation. This era of the RAC research is called *hard robotics* [1]. These robots tried to automate several construction processes in the house building and the civil construction. These robots were for interior building finishing, brick layer masonry, modular industrialized building's construction, road paver's sensor-based guidance, excavator's control, infrastructure inspection, tunnel and bridge construction, etc.

The "bubble economy" crisis en Japan and created overexpectation of the RAC strongly reduced investment in research activities during the last 3-4 years. Only few construction robots had success in the market. Nevertheless, the situation is changing now and new research RAC trends have been launching. The actual R&D activities are centring more in the *soft robotics*. It defines not as software only but also as hardware, but not in the machinery sense. It includes on-site sensory data acquisition and processing, human operator's field safety and security, chip-based process control, etc

2 HARD ROBOTICS STATE-of-the-ART

The main research activities of the RAC in the past decade were divided accordingly to applications into two large groups: civil infrastructure and house building [2]. Typical civil infrastructure robot applications are the automation of road, tunnel and bridge construction, earthwork, etc. In the group of house construction, main applications include building skeleton erection and assembly, concrete compaction, interior finishing, etc. Classification according to applications is consistent with other possible classifications, which divide RAC R&D activities according to the development of new equipment and processes or the adaptation of existing machinery to transform them into robotic system.

In this section several examples of the so called hard robotics are presented. In the group of civil infrastructure the examples are road pavers' sensor-based guidance, earthmoving control and infrastructure inspection. In the group of housing the examples are interior building finishing, brick layer masonry, column welding, modular industrialized building's construction.

2.1 Civil infrastructures

In the field of road construction, several projects had been developed over the last decade. They were mainly focused in the development of the new generation of semi-autonomous road pavers and asphalt compactors. The EU projects CIRC [3] and latter OSYRIS (www.osyris.org) had as the main objectives, based in the GPS and laser data, the semi-autonomous guidance of the machines and the quality control of pavers and roller processes by controlling the speed, temperature, layer thickness, travelled distance, etc. (Fig. 1). The coordination of several machines in order to improve productivity is also the objective of the project.

Figure 1. OSYRIS project sensor-based compactor.

In the field of earthwork the research is centred in the introduction of new control techniques to existing machinery like excavators, bulldozers, draglines, etc. One of the major exponents of this research area is the control by CSIRO of the 100-m tall walking crane used in surface coal mining [4]. The swing cycle of the dragline accounts for about 80 percent of time taken. The automatic swing cycle improves the efficiency of the machine, taking in mind that the bucket which weighs around 40 tonnes when empty and up to 120 tonnes when full, acts as a large pendulum and requires operator skill to control well (Fig. 2). The torque-force control during the excavation is also improving the productivity of the processes. The University of Sydney project [5] developed an automated excavator that accounts for interaction forces in analysing the required bucket motion therefore seems promising. As the bucket comes in contact with its environment, the contact force must be regulated such that it remains within a specific range by using specific intelligent control strategy (Fig. 3).

Figure 2. CSIRO's dragline project.

Figure 3. University of Sidney's automated excavator.

The periodic inspection and maintenance of the civil infrastructures was another important research activity. The inspection of building skeletons, complex roofs, off-shore platforms, bridges, etc. represents an extensive and valuable field of work. It is estimated that in the EU there are over 42.000 steel bridges with a replacement cost of 350 M€. The ROMA family climbing robots [6] able to travel in a complex 3D environment carry out several inspection sensors (laser telemeters, colour cameras) in order to transmit the field data to the "ground" system (Fig. 4). The key issue of these robots is the grasping method (grippers, electromagnets, suction cups, etc.) and the robot's adaptive control taking in mind gravity forces.

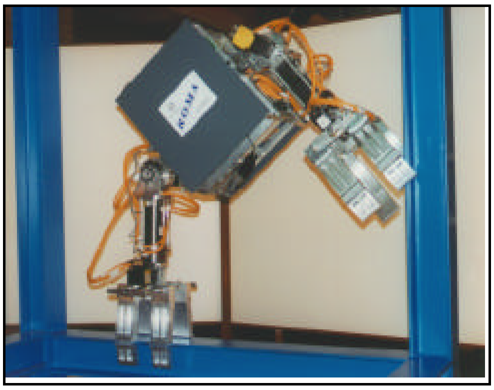

Figure 4. ROMA climbing inspection robot.

2.2 House building

Interior-finishing operations in the building are very time consuming and requires high degree of accuracy. There are several mobile manipulators able to perform variety of operations like extend, compact and control the thickness of the floor concrete, painting and steel column fire protection spraying, assembly of interior walls and ceilings, etc. Most of these robots are teloperated and perform only simple operations. The most representatives' robots of this type are Japanese ones. Two examples are presented: the "Mighty Hand" robot from Kajima (www.kajima.co.jp), which lifts heavy elements in construction as concrete walls, etc. (Fig. 5), and the SurfRobo from Takenaka (www.takenaka.co.jp), which automatically compact the concrete floor by using two sets of rotary floats (Fig. 6).

Figure 5. Kajima's interior wall assembly robot.

Figure 6. Takenaka's concrete compactor robot.

Several robots for automatic assembly of buildings were developed in the past. The effort had been done in the brick layer masonry. The EU project ROCCO developed a large-range (10 m reach) and high payload (up to 500 kg) hydraulic 6 DOF robot for brick assembly [7]. The robot is equipped with auto-tracking laser telemeter in the tip in order to perform prices (up to 5 cm) brick assembly. In this way the control system avoid important arm flexion. The robot performs the assembly sequence obtained by the planning software and needs an initialization process in order to know the bricks pallet position (Fig. 7).

Figure 7. ROCCO project brick assembly robot

The assembly of steel-based buildings is performing by welding, such as column-to-column and column-to-beam joints. The Japanese WR mobile robot performs a variety of column-to-column welding (Fig. 8). The columns can be of up to 100 mm in thickness and round-, square-, and H-shaped steel pipes, as well as box-sectional members. For column-to-beam welding, there is a combination welder/transport type which can run on decks and a type which can weld lower flanges from below.

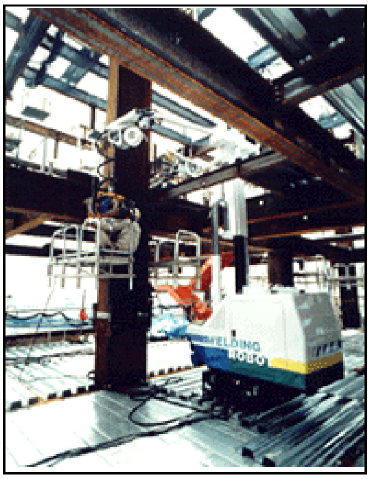

Figure 8. WR mobile robot for column welding

Figure 10. Bolder building transportation by water

Automation and robotization of the complete building erection is the most exciting experience. Applying to the high-rise building there were several Japanese projects. The most significant is the SMAT system developed by Shimizu [8]. It was used for construction of more than 30 stories office building. It consists of all-wheatear, full-robotic factory on the top of the building. The lift-up mechanism automatically raises the construction plant and at the same time raises the on-site factory, called *field factory* (Fig. 9). More recently the Dutch companies develop the new whole building erection technology but in opposite way of the previous system. The building is totally constructed in like factory environment and then transported to the final location. The 10 floor building called Bolder was transported by water in a three day operation (Fig.10).

Figure 9. SMART factory in the top of the building.

3 SOFT ROBOTICS TRENDS

As it was discussed before, *soft robotics* is not only limited to software itself but also includes other related technology as sensory data acquisition and processing, human operator's field safety and security, chip-based process control, etc. This section describes the main applications and some examples of the actual soft robotics trends. It is important to note that for real RAC applications the *soft robotics* must be balanced with the hard one.

3.1 Software integration

Software integration in the field of RAC is crucial for implementing the concept of the Computer Integrated Construction (CIC). The idea is to integrate in a common exchange format all the stages of the construction, i.e. from architect's desk and planning tools to site robots. The EU FutureHome projects develop the AUTOMOD3 system (Fig. 11) that integrates in a common CAD environment several tools like design, planning and automatic robot and machine programming [9]. Due the high level of conservatism of building designers, the main idea is to use the common 2D architectural design (drawings) and automatically transform it into 3D drawings. In this way it is possible to perform also automatically the modularization of the traditionally designed buildings. This process permits to industrialize the house-building by modular pre-fabricated construction.

Schedule management software packages are used more and more in construction. Nevertheless, its dynamic integration whit all the actors participate in the construction is not yet done. In a construction project, although the completion day is clearly decided, construction schedule is often changed by the weather or the actual progress situation of the project. When a difference arise between present state and the master schedule, it is necessary to adjust the construction schedule and to execute it immediately. The communication with part's produced factory, transport agents, stores and other suppliers is performing in real-time and in automatic way [10].

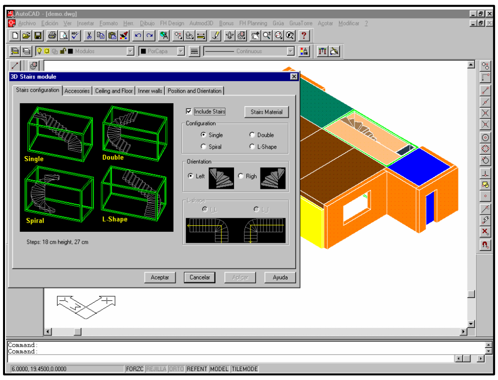

Figure 11. FutureHome integrated design and planning tools.

Mobile computing systems for data transfer between constructor managers and different web-sites have been implementing. The progress monitoring wireless mobile system permits to check the progress of the work. At the same time field note system is used to note unacceptable parts of works (Fig. 12). Inspection system is also used for inspect the result of construction. The document management system not only can communicate with the designers DBs in order to download the CAD drawings, but also permits the on-site modifications of these drawings. This soft technology is very useful and has a low cost which make them candidate for massive introduction in the site environment. The day when construction managers and operators carry only some paper drawings will be finished soon.

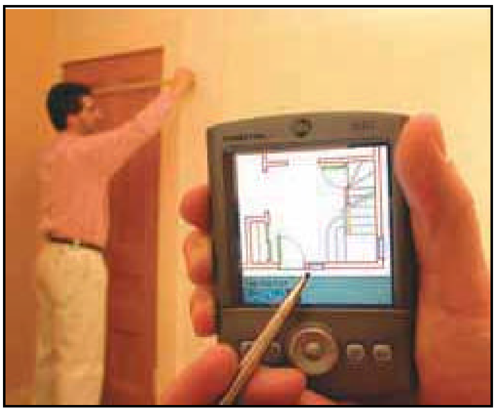

Figure 12. PDA-based document management system in the site environment.

3.2 VR systems

The Virtual Reality (VR) software together with an immersive projection display (IPD) allows construction managers to enter and interact with the contents of a full-scale building, before start or during the construction. The virtual mock-up offers first person presence, or the feeling that you're actually in the room when you're just standing in a space bounded by five large screens that surround you with a projected image. The virtual mock-up experience is real enough to enable welders, for example, to crawl under virtual structures and hit their heads on virtual pipes to determine if there's enough room to work. Several immersive VR systems were developed during the last years, like at the Penn State University (http://www.arl.psu.edu), at the NIST (http://cic.nist.gov/vrml/equip.html), etc.

In the world of construction operations analysis, the ability to see a 3D dynamic animation of an operation that has been simulated allows the experts, field personnel, and decision makers can discover differences between the way they understand the operation and the way the model developer understands it. The dynamic VR is more close to animation than geometrical visualization. The actual research is focusing on designing automated, discrete-event process simulation-driven methods to visualize construction operations and the resulting evolving products in dynamic, smooth, continuous, 3D virtual worlds. The discrete-event simulation systems, allows a computer to create a world that is accurate in time and space; and which shows people, machines, and materials interacting as they build constructed facilities.

Using VR system for simulation and training is another *soft robotics* area. For complex machines like excavators, the VR system needs not only to simulate the geometry and kinematics of the machine but also the terrain and the interaction between the machine and terrain [10]. The simulation of digging and driving over the terrain is the crucial test. The terrain model is generated with an elevation grid technique which specifies a height field over a uniform grid. If the size of an individual grid in the simulation is smaller than the footprint of the excavator the system will work correctly and the operator's sensation will be good. The system permits to be inside or outside the excavator cabin. To visually represent the digging process, the location of the bucket relative to the terrain and relative to the excavator needs to be known. To drive a complete *Caterpillar* 3D backshore simulator, please see in the web page http://www.howstuffworks.com/backhoe-loader.htm.

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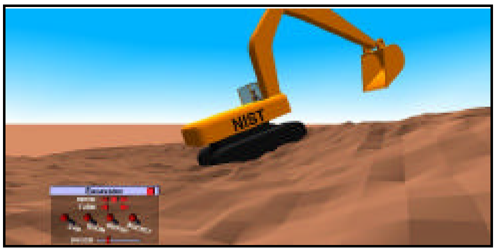

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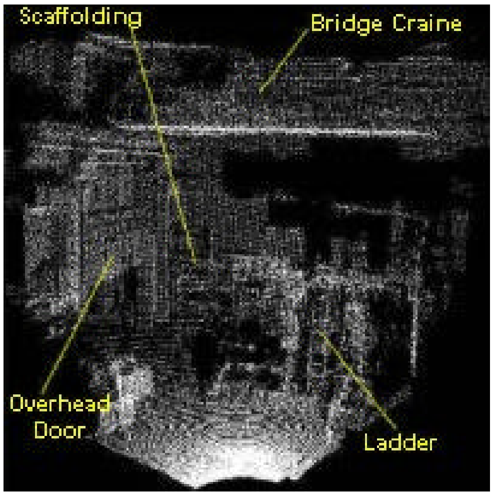
Figure 13. VR environment for excavators training system: a) inside the cabin, b) outside the cabin.

3.3 Sensory data acquisition and processing

One of the most promising are of research in *soft* RAC is the sensory data acquisition and processing. The use of sensor for modelling the environment and then use this data for processing is much valuable for the control of automatic construction machinery or robots. The LADAR (Laser Radar) on-site data acquisition was one of traditional research area at NIST [11]. Nevertheless, only recently this technology has important applications in the automatic excavation, truck guidance, topography and inspection. LADAR technology is based on the high precision pan-and-tilt mounted laser rangefinder with the frame rate at least 10 Hz (commonly 25 Hz). The range of the laser scanner is up to 150 m for objects with reflection coefficient grater than 80% and 50 m for objects with reflection coefficient grater than 10%. Once the data are registered, they are used to generate 3D models or surfaces (Fig. 14).

Evaluation of surface generation algorithms involves a three-part process. In the first part, the characteristics (accuracy, noise, and related uncertainties) of the sensor would be determined. This "calibration" would be performed in an indoor facility, which allows for a controlled environment. In the second part, mathematical procedures are used to determine the statistical uncertainties of particular calculations (e.g., volume) based on the results of the instrument calibration. In the third part, the characteristics of the algorithms used to generate the 3-D model would be determined (how well does it handle missing points, outliers, discontinuities, vertical surfaces, etc.).



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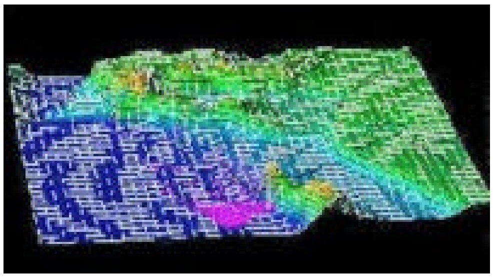

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Figure 14. NIST's LADAR data: a) environment map, and b) 3D reconstruction

The using of GPS for data collection is become very common. Some applications are very well known as automatic truck guidance, topography, etc. But nowadays low-cost facilities of using PDA-based GPS and web data transmission and collection make possible new applications. One of these applications is the GPS-aided earthquake monitoring. The data is collected via a GPS station with a circular antenna firmly fixed in a 4.5 tonne slab of 300 million year old sandstone from Yorkshire, which is in turn embedded almost three metres into the earth. This natural landmark is monitoring every 15 second via web.

3.4 Safety and secure operation

Thousands of construction workers are injury or killed in construction accidents each year. Some researches are conducting to look into new ways of improving the security and develop methods and reliable systems to detect possible failures and to avoid any harm to the workers, machines and installations. The main risk sources in on-site environment are collision with the machine transporting heavy and big pieces, falling, machine running over, etc.

In this *soft robotics* research, the compulsory safety helmet required for all workers in the site is used as the base to hold miniature positioning and communication instruments (Fig. 15) [12]. Bidirectional voice channel, portable GPS and micro-camera with video link are some of the helmets elements. The position and ID of each worker is communicated periodically via radio link to a monitoring station. These information is compared with a DB containing the tasks and processes to be perform in the site. If a given worker is at what the system considers a hazard source it acts according to the nature of source.

There are two basic secure levels: machine and human ones. Machine level refers to the failures in the machinery, possible erroneous operation, bad condition of the components, etc. As far as the human level is concerned, the objective is to prevent the operatives from suffering the accidents. The strategy to adopt consist in the definition of different safe and prohibited zones around the workers and the sources of danger, so that in the moment in which these areas comes into contact a danger situation is triggered and warning is generated. There are several actions to be done in this situation: advise the worker thought the voice commands, stops the machine movement via central computer, etc.

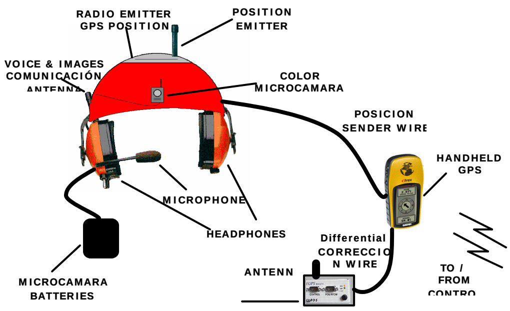


Figure 15. UC3M's active security system elements.

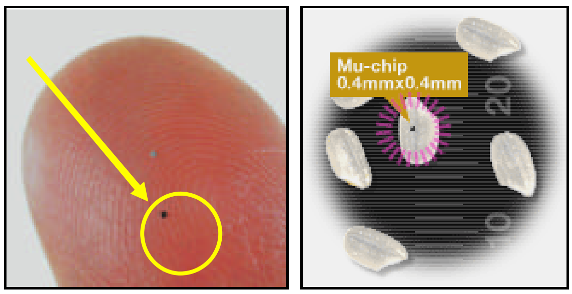
3.5 Part-oriented construction

One of the most innovative soft robotics applications in construction industry is the so called part-oriented construction [13]. The main idea is to link the fixed and temporary facilities of construction site (ground, cranes, field factories, etc.) with the parts-peoples dynamically changing world via information network. It means that the status, position and timing of parts and human operators in the site are known in every moment. Moreover, it is possible to dynamically plan, command, tracking and monitoring all the construction recourses.

To perform this monitoring each part, machine and operator has assigned an identification chip which wireless connects with external devices. This chip is a wireless semiconductor integrated circuit that stores an ID number in its memory (Radio Frequency Identification Device -RFID). The µ-chip developed by Hitachi is a micro-device with square of 0.4 mm that uses the frequency of 2.45GHz. It has a 128-bit ROM for storing unique ID (Fig. 16).

The system which controls whole the construction process is called glue logic. This system binds multiple application software modules, referred as "agents", developed and compiled separately, and coordinates those agents. As "glue logic" supports even notification and conditioning monitoring features based on active data scheme, users can easy build real-time event-driven application agents. The glue logic consists of two major parts: communication subsystem exchanging data with concurrently running agents and the data management subsystem.

Every part has attached µ-chip (which includes antenna). When a chip-implanted part passes through the gate, the gate reads the product URL. It determines what it is, when and in what state it is. The corresponding data point in the glue logic is then altered, which generates an event and a chain of succeeding actions. For communicates with human operators some of them carry a wireless PDA which is capable to connected to the main web server where glue logic is running and, at the same time, is capable to read µ-chip attached to the part. Moreover, the system is applied to automated handling of devices, by communication with automatic cranes and glue logic DB.



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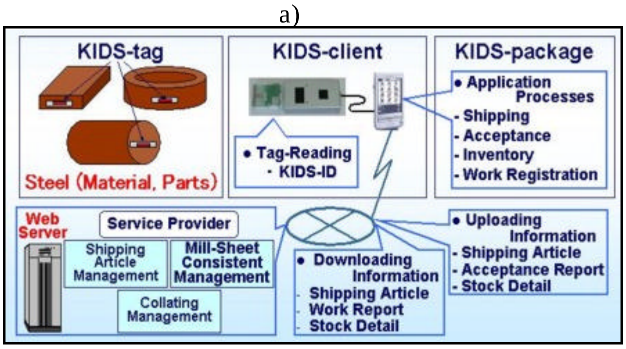

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Figure 16. *Hitachi's* RFID µ-chip a) in comparison with the human finger and rise grain, and b) their application for steel-based parts' tracking.

4. CONCLUSIONS

This paper presented the short-state-of-the-art in the area of hard robotics focusing in the new robots development and machine automation. This area was very strong during 90s. But actually it is balanced with the new emerging one called soft robotics. It is based on the software integration, simulation and VR, sensory-based monitoring and tracking, part-oriented construction, etc. These examples are the most representatives but not the unique ones. It is possible to mention other new soft applications like artificial life modelling of the construction process, life cycle engineering, RFID chip-robot interaction, etc.

The RAC's sciences and technology moves actually in the direction to soft robotics. It is not means that hard robotics is end, but their development is actually slowly. Integration and coordination of both hard and soft areas is the objective of the long-term research in the field of RAC. It is very welcoming that this research focus strategically appears in several national and regional research programs, like the EU 6th Frame Program. It is also supported in the inter-regional global program IMS.

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