Robotics and Automation in Construction

Ernesto Gambao (Polytechnical University of Madrid, Spain)
Carlos Balaguer (University Carlos III of Madrid, Spain)

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 gross domestic product (GDP) in industrialized countries is about 7-10%, including 2.7 M enterprises in the European Union (EU) [1]. This is comparable with the manufacturing industry but with double the investment in R&D for manufacturing [2]. Today, it is evident that the level of automation in construction is very low in comparison with current technological advances. This is why all the actors (researchers, companies, and administrations) must make new efforts to increase the automation level of this important sector [3].

Research activities in the field of robotics and automation in the construction industry are divided according to applications into two large groups: civil infrastructure and house building. Typical civil infrastructure applications are the automation of road, tunnel, and bridge construction; earthwork; etc. In the field of house construction, main applications include building skeleton erection and assembly, concrete compaction, interior finishing process, etc. Classification according to applications is consistent with other possible classifications, which divide R&D activities according to the development of new equipment and processes (robots, automatic systems, etc.) or the adaptation of existing machinery to transform them into robotic systems.

In the field of road construction, several projects have been developed over the last couple of years. The most representative project was the EU Computer Integrated Road Construction (CIRC) project (1997-1999) that dealt with the development of a new generation of autonomous road pavers and asphalt compactors [4]. These mobile machines (robots) extensively used GPS-based tracking technology for autonomous navigation. [5]. In road construction, the quality of the compacted material (asphalt) is essential and depends on the number of runs of the compactor and the uniformity of the energy distribution. Field management of the hot-mix asphalt process [6] is another important field of research in this area.

The current method of tunnel construction leads to fully automated work, in which several Japanese companies are very active. In this work, automated transportation (the driving head based on the parallel manipulator concept) and sensor-based navigation (by lasers, gyrocompasses, level-gauges, and inclinometers) is used in excavation machines [7]. For the construction of shield-type tunnels, automatic drive systems and segment installation using bolt-tightening robots are developed [8]. The shotcrete robot for rock support in the construction of mountain tunnels by concrete spraying [9] is another innovative project in the field.

The automatic or semiautomatic construction of bridges, dams, offshore platforms, and other big civil infrastructures is an important R&D field. The development of the 15-m range auto-conveying concrete system based on the SCARA robot concept for dam construction in Japan [10] or the development of a column-field-welding robot for bridge construction [11] using laser-based high-precision feedback for verticality control are two significant examples. Related to this field of application are several ongoing projects that deal with the architectonic design oriented to the automatic movement of civil infrastructures like roofs [12] and bridges.

The periodic inspection and maintenance of bridges 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 value of €350 M. This is why several research projects related to robotic inspection are ongoing. At North Carolina State University, an inspection system based on a four-DOF robot located on the end of a truck-mounted peer crane was developed [13]. A different approach was used at the University of Carlos III of Madrid by developing autonomous climbing robots [14] able to support and transmit onboard sensor data (image, laser, X ray, etc.)—the processing of which is yet another field of research [15], [16].

Earthwork research activities are focused towards the introduction of new control techniques to existing civil machinery: excavators, graders, etc. Dynamics and kinematics control together with the force/torque feedback in the excavator bucket [17], [18] are important issues towards robotic autonomous excavation [19]. Moreover, it is necessary to model the soil and obtain real-time terrain data using, for example, LADARs, as used in several projects at NIST [20]. Teleoperation of backhoe excavators, remotely operated using visual and force feedback [21], is very much appreciated by operators. These techniques are indispensable for the operation of big civil machines like 100-m boom-length draglines [22] or 25-ton CMUs excavators for autonomous truck loading [23].

Residential construction, in particular high-rise buildings, promise to be one of the biggest businesses of the future. House erection, especially for high-rise buildings, is a key issue. Several Japanese companies have developed innovative systems during the last decade. The SMART system, developed in 1992-1994 [24], was the first one. It was used for the construction of more than 30 stories. It consists of an all-weather, full-robotic factory on the top of the building. The lift-up mechanism automatically raises the construction plant. The continuation of this effort is the IF7 Japanese [25] and FutureHome EU projects [26].

For efficient house building, transportation and assembly devices for heavy and big parts are necessary. Several robots for automated assembly were developed during the last couple of years. The EU Robot Assembly System for Computer Integrated Construction (ROCCO) project (1992-1996) dealt with the development of a large-range, 10-m long, and 500-kg payload hydraulic robot with laser telemeter auto-tracking feedback [27]. Its main application is block assembly, similar to the BRONCO robot [28]. The control strategy of the very large range 22.5-m EMIR robot [29] is based on dynamic force feedback control, which takes into account the elasticity of the links. The UT's large range manipulator pays special attention to teleoperation aspects [30].

The automation of commercially available construction machines for the assembly of building parts is focusing on different types of cranes. The anti-swinging control of the tower cranes is one of the not-quite-solved problems. By introducing a suspender in the hook, controlled by gyroscopic moments [31], precision during movement is highly increased. Other techniques to avoid same problem are the use of a fuzzy controller [32] or input shaping strategy [33], thus reducing the danger to workers and improving efficiency.

Interior-finishing operations are very time consuming and require a high degree of accuracy. There are several mobile robots developed to compact and control the thickness of concrete. The overall control of the KIST floor robotic troweling system [34] introduces a network-based real-time distributed architecture under CAN in order to coordinate the fleet of robots. Painting is another important finishing task. Technion developed several painting robots [35] where the key problems are the spraying tools and the positioning the robot to maximize the painted area. In the area of interior assembly, the Waseda Construction Robot (WASCOR) project (1993-1997) [36] obtained significant results in the assembly of wall panels with mobile robots.

The need for prefabricated elements in house building increases every day, so the automatic manufacture of these elements is very important. The robot spraying system is used for the manufacturing of concrete and composite parts of the building, such as facade panels. Automatic spraying tool path planning, as well as robot singularity avoidance, have been treated [37]. The integration of masonry robots for brick and panel manufacturing is performed under the computer integral manufacturing concept [38]. Another important aspect of research activity in the field of house building prefabrication is the computer-aided architectural design of parts oriented to robotic manufacturing [39].

The examples of robotic applications in the construction industry mentioned above are not the only examples; numerous other projects are closely related to this area of research. More details can be found at http://www.iaarc.org and http://www.ncsu.edu/IEEE-RAS/RAS/TCparent.html (IEEE Technical Committee on Service Robots).

This issue's articles were selected for their technical level and innovation aspects, as well as according to their scope of coverage of the thematic areas of civil engineering and house building. Our intent is to cover different applications and technological aspects.

The article by Ha, Santos, Nguyen, Rye, and Durrant-Whyte describes the fully autonomous execution of excavation tasks in common construction, such as loading a truck or digging a trench. A 1.5-tonne hydraulic mini-exavator was used for field experimental work. The machine has been extensively modified to include a laser measurement system for scanning terrain. The dynamic model and implemented control strategy are presented.

The article by Oloufa presents a GPS-based automated quality control system for tracking pavement compaction. The system was designed to track a single compactor, and all calculations were done on board the compactor. A GPS-based positioning device is placed on the compactor. The main objective is to test paving surfaces that suffer from low density and cracking in order to avoid accidents and an uncomfortable ride.

The next article, by Chamberlain and Gambao, discusses an automatic system for concrete repair preparation. The system is based on high-pressure water blasting robots that are used to remove defective concrete in the preparation of repair work. The system incorporates sensing and control strategies that are robust in this harsh environment. The sensing technology is based on a nondestructive testing metal detector (covermeter).

In the article by Arai, Yuasa, Mae, Inoue, Miyawaki, and Koyachi, the hybrid cylinder/wire drive parallel manipulator for the transportation and assembly of heavy materials in an onsite construction environment are presented. The developed six-DOF prototype enlarges the limited workspace of the conventional parallel manipulator by replacing some cylinders with wires. A wire drive mechanism is analyzed using the force closure principle.

Finally, the results of the FutureHome project are presented in the article led by Balaguer. The article is focused on the development of the integrated construction automation concept for house building. The main objective is the modular design of buildings, keeping in mind their robotic erection. The robotized gantry crane is able to transport and assemble house modules with high-precision and in all weather conditions. A 1:3 scale model test-bed has been developed.

References

[1] Eurostat annuaire, 1999. [Online]. Available: http://europa.eu.int/comm/eurostat)

[2] ACEA report, 1999; and Euroconstruct report, 1998.

[3] C. Balaguer, "Open issues and future possibilities in the EU construction automation," in *Proc. IAARC Int. Symp. Robotics and Automation (ISARC'00)*, Taipei, Taiwan, 2000, pp. K21-32.

[4] F. Peyret, J. Jurasz, A. Carrel, E. Zekri, and B. Gorham, "The computer integrated road construction project," *Automat. Constr.,* vol. 9, no. 5-6, pp. 447-462, 2000.

[5] S. Sukkarieh, E.M. Nebot, and H.F. Durrant-Whyte, "A high integrity IMU/GPS navigation loop for autonomous land vehicle applications," *IEEE Trans. Robot. Automat.,* vol. 15, pp. 572-578, June 1999.

[6] H. Lee, "Toward a framework for field management of hot-mix asphalt (HMA) construction operation," Ph.D. dissertation, Univ. Wisconsin-Madison, WI, 1998.

[7] Komatsu, Ltd. Web site. [Online]. Available: http://www.komatsu.co.jp

[8] H. Ohno, K. Kazama, A. Higashide, A. Tokioka, and K. Tsuchiya, "Fully automated sysetm for shield tunneling under integrated control," in *Proc. IAARC Int. Symp. Robot. Automat. (ISARC'96)*, Tokyo, Japan, 1996, pp. 779-788.

[9] G. Girmscheid and S. Moser, "Fully automated shotcrete robot for rock support," *Comput. Aided Civil and Infrastructure Eng.,* vol. 16, no. 3, pp. 200-215, 2001.

[10] M. Baba, M. Takeda, and T. Nogiwa, "Development of auto-conveying system for dam concrete," in *Proc. IAARC/CIB/IEEE/IFAC Int. Symp. Robot. Automat. (ISARC'00)*, Taipei, Taiwan, 2000, pp. 27-32.

[11] K. Nisita, "The development of new type column-to-column welding robot at site," *Structural Technol.,* vol. 8, 1998.

[12] K. Kurita, F. Inoue, N. Furuya, T. Shiokawa, and M. Natori, "Development of adaptive roof structure by variable geometry truss," in *Proc IAARC/CIB/IEEE/IFAC Int. Symp. Robot. Automat. (ISARC'01)*, Krakow, Poland, 2001, pp. 63-38.

[13] S.J. Lorenc, B.E. Handlon, and L.E. Bernold, "Development of robotic bridge maintenance," in *Proc. IAARC Int. Symp. Robot. Automat. (ISARC'97)*, Pittsburgh, PA, 1997.

[14] C. Balaguer, A. Gimenez, J.M. Pastor, V.M. Padron, and M. Abderrahim, "A climbing autonomous robot for inspection application in 3D complex environments," *Robotica*, vol. 18, pp. 287-297, 2000.

[15] F. Weise, et al., "Nondestructive sensors for inspection of concrete structures with climbing robots," presented at the Int. Conf. Climbing and Walking Robots (CLAWAR'01), Karlsruhe, Germany, 2001.

[16] Industrial and Materials Technologies Automated Inspection and Maintenance of Steel Structures (AIMS) Web Site. [Online]. Available: http://www.isw.uni-stuttgart.de/projekte/aims/

[17] D. Bradley and D.W. Seward, "The development, control and operation of an autonomous excavator," *J. Intell. Robot. Syst.,* vol. 21, no. 1, pp. 73-97, 1998.

[18] S. Tafazoli, P.D. Lawrence, and S.E. Salcudean, "Identification of inertia and friction parameters for excavator," *IEEE Trans. Robot. Automat.*, vol. 15, pp. 966-971, Oct. 1999.

[19] E. Keskinen, S. Launis, M. Cotsaftis, and Y. Raunisto, "Performance analysis of drive-line steering methods in excavator-mounted sheet-piling system," *Comput. Aided Civil and Infrastructure Eng.,* vol. 16, no. 4, pp. 229-238, 2001.

[20] W. C. Stone, G.S. Cheok, K.M. Furlani, and D. Gilsinn, "Object identification using bar codes based on LADAR intensity," in *Proc. IAARC/IEEE/IFAC Internat. Symp. Robot. Automat. (ISARC'01)*, Krakow, Poland, 2001, pp. 103-108.

[21] A. Barrientos, O. Luengo, and A. Moran, "Teleoperated backhoe excavator with haptic control," in *Proc. IAARC/IEEE/IFAC International Symposium on Robotics and Automation (ISARC'99),* Madrid, Spain, 1999, pp. 565-570.

[22] P.R. Ridley and P.I. Corke, "Dragline automation," in *Proc. IEEE Int. Conf. Robot. Automat. (ICRA'01),* Seoul, Korea, 2001, vol. 4, pp. 3742-3747.

[23] A. Stenz, J. Bares, S. Singh, and P. Rowe, "A robotic excavator for autonomous truck loading," *Autonomous Robots*, vol. 7, no. 2, pp. 175-188, 1999.

[24] Y. Miyatake, "SMART system: A full-scale implementation of computer integrated construction," presented at the IAARC Int. Symp. Robotics and Automation (ISARC'93), Houston, TX, 1993.

[25] Intelligent Manufacturing Systems Web site. [Online]. Available: http://www.ims.org/index_projects.html

[26] FutureHome Web site: Available: http://www.cv.ic.ac.uk/futurehome/

[27] E. Gambao, C. Balaguer, A. Barrientos, R. Saltaren, and E.A. Puente, "Robot assembly system for the construction process automation," in *Proc. IEEE Int. Conf. Robotics and Automation (ICRA'97),* Albuquerque, NM, 1997, vol. 1, pp. 46-51.

[28] G. Pritschow, M. Dalacker, J. Kurz, and M. Gaenssle, "Technological aspects in the development of a mobile bricklaying robot," *Automat. Constr.,* vol. 5, no. 1, pp. 3-14, 1996.

[29] H.B. Kuntze, U. Hirsch, A.Jacubasch, F. Eberle, and B. Goller, "On the dynamic control of a hydraulic large range robot for construction application," *Automat. in Constr.,* vol. 4, no. 1, pp. 61-74. 1995.

[30] G.A. Thomas, "Development of an advanced control system for the University of Texas Large Hydraulic Manipulator," Ph.D. dissertation, Univ. Texas, Austin, TX, 1995.

[31] T. Wakisaka, N. Furuya, Y. Inoue, and T. Shiokawa, "Automated construction system for high-rise reinforced concrete building," *Automat. Constr.,* vol. 9, no. 3, pp. 229-250, 2000.

[32] H.H. Lee, S. Choi, "A model-based anti-swinging control of an overhead crane with high hoisting speeds," in *Proc. IEEE Conf. Robotics and Automation (ICRA'01*), Seoul Korea, 2001, vol. 3, pp. 2547-2552.

[33] W. Singhose, "Command generation for flexible systems," Ph.D. dissertation, MIT, Boston, MA, 1997.

[34] M. Hwang-Bo, B.J. You, and S.R. Oh, "Development of an unmanned autonomous concrete floor robotic troweling system," in *Proc. IAARC/IEEE/IFAC Int. Symp. Robotics and Automation (ISARC'99)*, Madrid, Spain, 1999, pp. 79-84.

[35] A. Warsawski, Y. Rosenfeld, and I.M. Shohet, "Autonomous mapping system for an interior finishing robot," *ASCE J. Comput. Civil Eng.,* vol. 19, no. 1, 1996.

[36] M. Handa, Y. Hasegawa, and H. Matusda, "Development of interior finishing unit assembly system with robot," *Automat. Constr.,* vol. 5, no. 1, pp. 31-38, 1996.

[37] L.F. Peñín, C. Balaguer, J.M. Pastor, F.J. Rodriguez, A. Barrientos, and R. Aracil, "Robotized spraying of prefabricated panels," *IEEE Robot. Automat. Mag.,* vol. 5, pp. 18-29, Sept. 1998.

[38] C. Hanser, "Automation concept for the pre-fabrication of masonry elements," Ph.D. dissertation, Tech. Univ., Vienna, Austria, 1994.

[39] J.M. Pastor, C. Balaguer, F.J. Rodriguez, and R. Diez, "Computer-aided architectural design oriented to robotized facade panels manufacturing," *Comput. Aided Civil Infrastructure Eng.,* vol. 16, pp. 216-227, 2000.

Ernesto Gambao is with the Automatic Control Department of the Universidad Politécnica de Madrid (e-mail: gambao@disam.upm.es).

Carlos Balaguer is with the University of Carlos III in Madrid, Spain (e-mail: balaguer@ing.uc3m.es).