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Automation in Concrete Construction

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18.1 Categories of Construction Automation

Concrete construction automation is a broadly defined planning and technical endeavor that includes
two distinct areas. The first is development of programmable (i.e., robotic) hardware for the execution
of construction work tasks; significant progress has been achieved in equipment navigation, locomotion
systems, and concrete-placement systems. The second is development of computer-based tools for effi-
cient and optimal planning, design, construction, and operation of concrete structures. Of particular
importance is the development and practical application of tools for design visualization, quantity takeoff
and cost estimation, generation of work schedules and job cost reports, design–construction integration,
construction task planning, optimal resource management, and design for constructability and main-
tainability of concrete structures.

18.2 Automated Construction Equipment and Related Hardware

Construction robotics are now beyond the initial design and academic discourse stages, which was not
the case throughout the 1980s and early 1990s (Skibniewski, 1988, 1996). A number of institutions
worldwide have developed prototype hardware for various applications that are now in field testing or

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initial implementation stages. Currently, the most mature applications of robotics in concrete construction include concrete screeding, surface finishing, scrubbing, and cleaning. Japanese construction firms that have developed their own prototypes of such machines include Obayashi Corp., Taisei Corp., Takenaka Corp., and Shimizu Corp.

An automatic concrete screeder has been developed by Takenaka Corp. (see Figure 18.1). The girder-mounted machine has an automatically controlled screeding tool that operates sequentially along a girder running over a self-shifting rail. When the tool reaches the edge of the rail, the rail is shifted forward automatically after invoking the rail-shifting function on the machine controller. The entire screeder has a modular design and can be manually assembled on the construction site. Assembly and disassembly can be accomplished by two or three workers in about 4 hours. The screeding tool includes a screw to perform concrete leveling by transporting surplus concrete to the side. This is done using a vibrating board that ensures an adequately horizontal surface when the concrete is shifted to the side. The maximum weight of the screeding tool is approximately 130 kg. The girder support structure for the trowel is also

![Figure 18.1](image-url)
modular, with parts ranging from 2 to 3 m in width. The traveling saddle for the trowels is located under the girder. The maximum weight of the girder components is approximately 50 kg. The control system for the screeder includes an inclinometer, a laser leveling device, and a rotary encoder (Okuda et al., 1992). The screeding capacity of the machine is approximately 350 m² of a slab area per hour, or 35 m³ of fresh concrete mix per hour on a slab with a thickness of 18 cm.

An example of a concrete surface finishing robot, the Flatkin by Shimizu Corp., is shown in Figure 18.2. The Flatkin consists of travel rollers, a power trowel, a controller, and a guard frame. A pair of travel rollers is attached at the bottom of the main body of the robot. The robot can move back and forth or left and right, using DC motors to drive the rollers. The power-trowel mechanism has three supporting arms. Each arm has a rotating trowel assembly with three trowels each. A gasoline engine is
FIGURE 18.2  Concrete surface finishing robot by Shimizu Corp.

FIGURE 18.3  High-rise building automation by Obayashi Corp.
used as a power unit to drive the trowel assemblies, so the trowel assemblies rotate around the axis and simultaneously rotate around the entire traveling device. The ratio of the rotation speed of the trowels to the revolution speed of the robot around its own axis is approximately 10 and above. The angle between the concrete surface and the trowel can be adjusted by a cam mechanism. This angle is usually changed depending on the hardness of the concrete surface to be finished. The robot is equipped with a guard frame with a touch sensor mounted as a safety device. In addition to the engine for the trowel, the robot has a small generator that enables the elimination of electric power cables, thereby increasing its mobility. The Flatkin can be operated by radio remote control, which is a useful feature for changing the trowel blade positions depending on the hardness of concrete encountered in a given work area. The robot work output is approximately 600 to 700 m² of concrete surface area per day, utilizing two operators in the process. The productivity of the robot is four to five times higher than that of human workers utilizing mechanized walk-behind trowels and manual tools (Ueno et al., 1988).

A partially automated overhead construction factory system for high-rise reinforced concrete frame buildings had been developed by Obayashi Corp. Their Big Canopy system integrates a synchronously climbing canopy that houses semiautomated overhead cranes, prefabricated concrete paneling components, computerized management of storage and retrieval of materials on-site, and a semiautomated structural assembly (see Figure 18.3). The canopy covers the entire story of the building being erected to protect workers from severe weather and to produce a safer work environment. Tower crane posts are used as four columns that support the canopy. Raising of the canopy is performed by the climbing facility of the tower cranes. Safety of motion is maintained by synchronized control. A high-speed construction lift and three hoist cranes are combined to deliver the structural components and materials for assembly. The material is raised to the working floor by the lift and passed to the hoist on the delivery girder. The movement of the hoist is fully automated for maximum work efficiency. Upon completion of the building construction, the canopy is disassembled on the top of the building. The external frame is then lowered and then safely disassembled on the ground.

Among the automated surveying technologies relevant to concrete construction, the Consortium for Advanced Positioning Systems (CAPS) has engineered an application of a laser-based positioning device called Odyssey™, developed by Spatial Positioning Systems, Inc. (SPSi) (Figure 18.4). The system has two primary components: transmitters and receivers. At least two transmitters are required to provide
positioning signals to a receiver; however, any number of receivers can utilize the positioning signals simultaneously. The transmitters can be set up at convenient locations and generally aimed at the work site. Existing benchmarks are used to calibrate the system using any local coordinate system. Each receiver is composed of two lenses mounted on a pole, a processor, a data entry and retrieval system, and a power supply.

The two lenses form a line, and the position of the lenses and the known geometry of the pole allow the point of position measurement to be projected to the end of the pole. Because the position of the tip of the pole does not change if the pole is slanted, rotated, turned upside down, or sideways, the position of any point that the user touches with the receiver is accurately and instantly measured. SPSi system software provides basic functions such as distance between two points, areas, volumes, or angles, although the integrated site positioning system combines real-time coordinate data from the Odyssey™ system with computer-aided design (CAD) design data. The combination of real-time coordinate measurement and CAD representation allows field position and graphical design data to be provided simultaneously to the user. A variety of applications for this system exist in new construction as well as in retrofit projects; for example, in facility characterization, the comparison of as-designed with as-built physical parameters is a large application area in itself. Other applications include industrial plant outage planning and simulation, modular planning, fabrication and construction, consistent site control during construction, providing plant database baselines, and real-time position feedback for automated construction equipment (Beliveau, 1996).
18.3 Economics and Management of Robots

The most decisive factor when considering using a robotic application in construction is its impact on the overall cost of the concrete construction process (Skibniewski, 1988). The promising areas of application are in tasks where the work volume, high repetition, and simple control requirements result in promising robot automation potential. Such tasks include concrete surface treatment (e.g., cleaning, painting, sandblasting), inspection (e.g., nondestructive testing of concrete and reinforcement steel and assessment of ceramic tile adhesion to concrete surfaces), and concrete placement.

Robot-related costs to be reconciled during the analysis include capital costs and operating costs. The capital costs include research and development expenditures (hardware and software, work-system engineering, calibration, and field hardening). Operating costs include energy, maintenance, downtime, repair, tooling, setup, dismantling, transportation, operator, and other related expenditures. Robot-related benefits include construction labor and material savings, improved work quality, extension of work activity into additional locations and time periods, and possibly improved productivity. Details of the economic analysis of construction surface finishing tasks can be found in Skibniewski (1988).

As can be expected from the conditions under which the construction industry operates, the most important decision factor for robot implementation will be a short-term profit potential resulting from labor savings through productivity improvement and possibly through increased construction quality. Most conservative construction firms will be unlikely to invest in robot research and development and will rely on robotics technology developed by commercial robotic systems houses. Such robots will then be either sold or leased by commercial vendors operating in the construction equipment market.

A major difficulty that construction firms will initially face is estimating the robot costs and benefits, as outlined above. The estimation process will improve as more experience with particular robot applications is gained. Detailed information on the cost and benefit items for various robot applications in typical job-site settings can accelerate the pace of robotization if it is made available to all interested construction firms. Future construction robot equipment vendors will be well positioned to fulfill this function in cooperation with robot system developers and manufacturers. When more robotics become available for use on construction sites, significant challenges to both management and technical staff will emerge. For the reasons outlined above, robots must be managed wisely and perform at a high quality level to ensure maximum economic benefits for the contractor’s firm.

Despite a number of advantages over traditional methods of performing construction tasks, robots are currently, and will continue to be in the near future, in short supply in comparison to other construction equipment. Thus, robots should be regarded as a scarce resource and their use should be maximized to their full operating potential. By maximizing robot capabilities on as many construction projects as possible, the economic benefits of robot use can be easier to attain; consequently, robot development costs can be recovered faster, and robot use can spread to other applications and types of construction tasks. A hypertext-based optimization program called the Construction Robotics Management System (CREMS) has been developed for that purpose. As shown in Figure 18.5, it consists of four modules: Construction Task Analysis, Robot Capability Analysis, Robot Economic Evaluation, and Robot Implementation Logistics (Skibniewski and Russell, 1991).

Automation in construction still constitutes a difficult technical and managerial challenge; however, potential benefits may be significant in this industry. Due to the lack of investment in research and development by construction firms in most industrialized countries except Japan, in combination with other factors, the industry has been experiencing difficulties in introducing and adopting new technologies at the project site level. To facilitate a more comprehensive impact of automation on the construction industry in the future, further research and development are essential. In particular, more attention should be focused on the redesign of construction sitework environments to enable direct technology transfer from other industries to construction, rather than on development of customized automated construction equipment that would closely resemble the humanlike performance of traditional construction tasks (Skibniewski and Nof, 1989). Sound methodologies for systematic technology transfer and
evaluation are also necessary (Gaultney et al., 1989), particularly those utilizing the recent advances in computing technologies (Hijazi and Skibniewski, 1989). Better quality constructed products will increase the competitiveness of concrete construction firms involved and can ultimately lead to greater demand for their services. As research and development of construction robotics systems continue, the latest developments are regularly reported in annual symposia on automation and robotics in construction (see, for example, Cho et al., 2006) and in Automation in Construction, a bimonthly international research journal published since 1994.

18.4 Computer-Aided Design

18.4.1 Traditional Architectural CAD Modeling

Reinforced concrete (RC) structural facility delivery processes include the design and drafting of various sectional views, on drawing sheets, as two-dimensional drawings. Even a small design modification requires time-consuming redrawing of various sectional views, along with detailed rebar specifications. The emergence of traditional computer-aided design (CAD) systems changed the time-consuming manual design and drafting process into a series of keystrokes and mouse drags-and-clicks on a computer. As basic operations such as drawing and erasing a line, arc, etc. are much faster on a computer, traditional CAD systems reduced the costs of redrawing that resulted from design modifications. Traditional CAD systems require manual interpretation of the information pertaining to a given RC structural facility; for example, a given RC structural component such as beam is represented by several projections along with a set of symbols. This representation process requires manual interpretation not only during the design stage, which provides input of geometric and symbolic information, but also during the construction stage, which reproduces the exact shapes and configurations intended during the design stage. Further, the shapes and configurations are manually interpreted during the design and construction stages by different sets of people with widely varying knowledge and skills. In cases of complex reinforcement configurations—resulting from either the shape of the structure or special requirements such as earthquake resistance—total misinterpretation of shapes and configurations is possible during the construction stage, resulting in costly redesigns and rework. More advanced solid-modeling approaches, currently not prevalent in the RC structure domain, employ specialized representation schemes that would facilitate the interpretation process by capturing the shape information pertaining to a given design object. A brief discussion of various solid-modeling approaches is provided below.
18.4.2 Solid Geometric Modeling

A solid geometric model is an unambiguous and informationally complete mathematical representation of the physical shape of an object in a form that a computer can easily process (Mortenson, 1985). Topology and algebraic geometry provide the mathematical foundation for solid modeling. Computational aspects of solid modeling include data structures and algorithms from computer science and application considerations from the design and construction of engineering projects. The following techniques are available for the solid modeling of civil engineering facilities (Requicha, 1980):

- Primitive instancing
- Cell decompositions
- Spatial occupancy enumeration (SOE)
- Constructive solid geometry (CSG)
- Sweep representations
- Boundary representation (B-Rep)

18.4.2.1 Primitive Instancing

The primitive instancing modeling technique consists of an independent approach to solid-object representation in the context of the group technology (GT) paradigm. The modeling approach is based on the notion of families of objects, each member of the family being distinguishable by a few parameters. Columns, beams, and slabs can be grouped as separate families in the case of general buildings. Each object family is called a generic primitive, and individual objects within a family are called primitive instances (Requicha, 1980).

18.4.2.2 Cell Decompositions

Cell decompositions are generalizations of triangulations. Using the cell decomposition modeling technique, a solid may be represented by decomposing it into cells and representing each cell in the decomposition. This modeling technique can be used for the analysis of trusses and frames in industrial and general buildings, bridges, and other civil-engineering structures. In fact, the cell decomposition technique is the basis for finite-element modeling (Mortenson, 1985).

18.4.2.3 Spatial Occupancy Enumeration

The spatial occupancy enumeration (SOE) technique is a special case of the cell decomposition technique. A solid in the SOE scheme is represented using a list of spatial cells occupied by the solid. The spatial cells, called voxels, are cubes of a fixed size that lie in a fixed spatial grid. Each cell may be represented by the coordinates of its centroid. Cell size determines the maximum resolution. This modeling technique requires large memory space, thereby leading to inefficient space complexity; however, this technique may be used for motion planning of automated construction equipment under the complete information model (Requicha, 1980).

18.4.2.4 Constructive Solid Geometry

Constructive solid geometry (CSG), often referred to as building-block geometry, is a modeling technique that defines complex solids as a composition of simpler primitives. Boolean operators are used to execute the composition. CSG concepts include regularized Boolean operators, primitives, boundary-evaluation procedures, and point membership classification. CSG representations are ordered binary trees. Operators, which may consist of rigid motion, regularized union, intersection, or difference, are represented by nonterminal nodes. Terminal nodes are either primitive leaves, which represent subsets of three-dimensional (3D) Euclidean space, or transformation leaves, which contain the defining arguments of rigid motions. Each subtree that is not a transformation leaf represents a set resulting from applying the motional and combinational operators to the sets represented by the primitive leaves. The CSG modeling technique can be adopted to develop computer-aided design and drafting (CADD) systems for civil-engineering structures. It can be combined with primitive instancing that incorporates the group
technology paradigm to assist the designer. Although the CSG technique is most suitable for design-engineering applications, it is not suitable for construction-engineering applications as it does not store the topological relationships required for construction process planning (Requicha, 1980).

### 18.4.2.5 Sweep Representation

The sweep representation technique is based on the idea of moving a point, curve, or surface along a given path. The locus of points generated by this process results in one-dimensional, two-dimensional, and three-dimensional objects, respectively. Two basic ingredients are required for sweep representation: an object to be moved and a trajectory to move it along. The object can be a curve, surface, or solid. The trajectory is always an analytically definable path. The two major types of trajectories are translational and rotational (Mortenson, 1985).

### 18.4.2.6 Boundary Representation (B-Rep)

The boundary-representation modeling technique involves representing the boundary of a solid by decomposing it into a set of faces. Each face is then represented by its bounding edges and the surface on which it lies. Edges are often defined in the two-dimensional parametric space of the surface as segments of piecewise polynomial curves. A simple enumeration of the faces of a solid is sufficient to unambiguously separate the solid from its complement; however, most boundary-representation schemes store additional information to aid feature extraction and determine topological relationships. The additional information enables intelligent evaluation of CAD models for construction process planning and the automated equipment path planning required in computer-aided design/computer-aided construction (CAD/CAC) systems (Kunigahalli and Russell, 1995a; Kunigahalli et al., 1995; Requicha and Rossignac, 1992). A boundary-representation technique that stores topological relationships among geometric entities is most suitable for computer-aided generation of construction process plans. Primitive instancing, sweep representation, and CSG techniques are useful in developing user-friendly CAD software systems for design of civil-engineering structures. CAD systems that incorporate CSG or the primitive instancing technique during the interactive design process and that employ the boundary-representation technique for internal storage of design information are efficient for use in CAD/CAC systems (Kunigahalli and Russell, 1995b).

### 18.4.3 Solid Modeling of Reinforcing Elements

#### 18.4.3.1 General

The shape of the boundary of a reinforcing element corresponds to a solid cylindrical primitive. A solid cylindrical primitive consists of three faces, three edges, and two vertices. A boundary-representation scheme must account for storage and manipulation of these topological entities. A boundary-representation scheme, the rectangle adjacency graph (RAG), supports solid modeling of reinforcing elements for various structural components such as beams, columns, and slabs. A brief description of the RAG modeling approach for reinforcement detail is described next. A more detailed description can be found in Kunigahalli (1997).

#### 18.4.3.2 Description of RAG Scheme for Reinforcement Detail

**18.4.3.2.1 Beam (or Column) Components**

An RC beam or a column component consists of longitudinal bars to resist bending moment and stirrups or ties to resist shear force. The portion of a beam or column having the same configuration of longitudinal reinforcement is called a region. The geometric and topological information regarding reinforcement detail in a given region of a beam or column component is stored in a structure known as a Beam_Column_Region. The information regarding the boundary and reinforcement detail of a beam or column component and the connectivity of a beam or column component to its adjoining structural joints is stored in a structure known as the Beam_Column_Component.

The Beam_Column_Component structure contains a beam identification number, pointers to two adjacent structural joints, a pointer to a Face_Table structure that stores the boundary representation
(B-rep) of a beam or column component itself, and a pointer to a list of Beam_Column_Region structures. A parent pointer included in the Beam_Column_Region structure enables faster identification of the relative location of a region with respect to a complete RC-framed structure. Long_Circular_List and Loop_List store geometric and topological information pertaining to longitudinal reinforcement and stirrup or tie reinforcement, respectively.

The geometric and topological information regarding an individual reinforcing bar in a given region $i$ is stored using an Edge_Face structure that contains a pointer to the parent region and an enumerated type to uniquely identify an individual longitudinal bar in a given region. Geometric and topological information pertaining to lap-spliced bars are stored using a separate structure known as the Splicing_Rebar. The Edge_Face structures of longitudinal bars in a given region $i$ are stored in a circular list. A specification for the ordering of the circular list and labeling of longitudinal bars using the enumerated types has been provided to ensure an unambiguous representation.

There can be more than one loop of stirrup/ties to resist the shear force at a given cross-section of a beam or column component. The spacing of loops, and in some cases configurations of the loops of stirrups or tie bars themselves, may vary along the length of a given region. Geometric information pertaining to the vertices and faces is stored using floating point numbers. The information regarding the identified edge of a stirrup or tie reinforcing bar is stored using a pointer to an Edge_Type structure. The edge-to-edge and edge-to-contact-vertex topological relationships between a stirrup or tie bar and a longitudinal bar at the location of a standard hook can also be stored using a tailored structure designed specifically for storing hook information.

18.4.3.2.2 Slab Component

The RAG scheme supports solid modeling of reinforcement detail pertaining to a slab component, designed using one-way and two-way slab theories, that consists of longitudinal reinforcing bars to resist positive bending moment, negative bending moment, and torsion at the four corners. The reinforcement for positive bending moment and torsion are typically provided in two layers of bars—namely, upper and lower—that are placed along the two principal orthogonal directions $x$ and $y$. There exists a boundary edge-to-edge contact between a given longitudinal bar and every other longitudinal bar placed in the other (orthogonal) direction. Negative bending moment reinforcement for a slab normally results in edge-to-edge contacts with longitudinal bars near the top faces of the beams enclosing the slab.

The geometric and topological information pertaining to a reinforcing bar in a slab component can be stored using an Edge_Face_Slab structure in the RAG scheme that stores the bar as an enumerated type. The enumerated bar type enables identification of appropriate topological relationships that must be stored. The direction of a given longitudinal bar is also stored using another enumerated type. As only two types of boundary edge-to-edge relationships occur in the case of slab-reinforcing elements, an array of only two elements that contain self-pointers is provided to maintain edge-to-edge topological relationships. The structures of longitudinal bars in a slab are arranged as lists ordered in the two principal directions $x$ and $y$. Two such lists in orthogonal directions, which are confined within the boundary of a slab component, give rise to a rectangular grid structure. Thus, positive bending moment and torsional reinforcement in a slab component results in a total of five grid structures. Negative bending moment reinforcement for a slab component forms four lists, two in the $x$-direction and two in the $y$-direction, respectively.

18.4.4 Computerized Engineering Model

Although solid modeling approaches try to capture the shape of a given design object, the focus still remains on the geometric and topological information pertaining to the design object. A true engineering model, however, must also account for project-specific information pertinent to the model, the semantic relationships between various components of the model, and context-specific information associated with a given engineering domain. This requirement gave birth to a whole new concept that utilizes the object-oriented paradigm to allow incorporation of domain-specific expertise into a CAD application (BSI, 1996).
18.4.4.1 Object-Oriented CAD Modeling

An engineering facility-delivery process involves various participants such as owners, architects, structural designers, and construction contractors. These participants often work on different hardware and operating systems. In large engineering organizations, it is not uncommon for different groups using different hardware and operating systems to work on a single engineering project. Successful implementation of computer-integrated construction (CIC) concepts requires that the CAD data originating in one environment must be usable in any other environment without translation. Further, to support CIC concepts, a CAD system must archive a model in such a way that it can be reactivated after years or decades—for operation and maintenance or renovation purposes—without depending on the hardware or operating systems used during the model-creation process. Such a capability would facilitate smooth progression of users to more cost-effective hardware and operating systems of the future. An object-oriented CAD system that supports CIC concepts must also be capable of handling large datasets. Further, information pertaining to objects (e.g., a beam) present in a project model must be in a consistent state at all times during a CAD session. This is achieved by making sure that the beam information is always accessed and modified by the schema that defined and created the beam object.

The horizontally fragmented nature of the architecture design/engineering/construction (A/E/C) industry requires simultaneous sharing of a given project model by many users for different purposes. For example, let us consider a single beam in a project model. A structural designer may need to modify model information such as the depth of a beam, diameter and spacing of stirrups, and diameter and number of longitudinal bars at the soffit. On the other hand, a rebar subcontractor needs only to query the number and diameter of longitudinal bars, diameter and spacing of stirrups, and grade of concrete and steel. Further, a formwork subcontractor would typically be interested in a query related to the surface area that results from the beam dimension. Apart from allowing tailored intelligent views for different project participants, an object-oriented CEM that supports CIC concepts must ensure that modifications to a project model are properly coordinated and the model is kept in a consistent state at all times during the facility-delivery process. A concrete engineering project typically involves collaboration between experts in several domains such as design, rebar detailing, formwork installation, rebar placement, and concrete placement. An object-oriented CEM must facilitate integration of the information created by each of the domains and allow easy and consistent access by users in other domains (e.g., HVAC, electrical, and mechanical systems). Hence, it should be possible for one schema to reference information defined and maintained by another schema within a given project model that includes schemas that support several disciplines such as architecture, structure, HVAC, construction, and operation and maintenance.

18.4.4.2 Example Object-Oriented CAD System

Objective MicroStation is an example system that addresses the requirements of an object-oriented CAD system and supports the concepts of computer-integrated construction. It includes a schema implementation language called ProActiveM, which is an object-oriented programming language that allows the engineering application developers to include domain-specific expertise by creating schemas tailored to model domain-specific information. A rebar design and detailing application, for instance, can focus on modeling domain-specific information such as spacing, hook location and type, grade of steel, and lap splicing.

18.4.4.3 Internet CAD

Downloading standard formwork components from a formwork vendor’s website and attaching them to an existing CAD model to check if readily available formwork components fit the designed model geometry is not far from reality with the availability of an Internet CAD system such as MicroStation. Internet CAD supports an Internet programming environment that is simple, is active (i.e., works on all platforms), and possesses web-distribution functionality (Bentley, 1996). Java is an Internet programming language that was developed by Sun Microsystems. The Java programming language allowed inline sound and animation in a web page for the first time. Java is not just a Web browser with special features but is also a programming language for distributed application. Java allows adding new types of content and
the codes necessary to interact with that content; however, Java does not allow two aspects necessary for web-based manipulation of CAD models: maintaining active CAD models and automatic transaction management. ProActiveM, developed by Bentley Systems, Inc., includes all the functionalities of Java programming language and supports automatic transaction management and maintenance of active CAD models. By augmenting CAD systems, such as MicroStation, with an Internet programming language, such as ProActiveM, civil engineers can create desktop sites to work with active CAD models of a given project located at a remote geographic site (Bentley, 1996).

### 18.4.4.4 Example Rebar Modeling Systems

**Geopak® rebar** transforms the MicroStation CAD system into a rebar design and detailing system for reinforced concrete structures. Modeling of any regular or irregular reinforcement arrangements that include many configurations of rebar such as straight bars, stirrups, circular and spiral ties, and radial reinforcement is supported. Geopak provides the tight coupling of a given structural component with the rebar model used to reinforce the structural component. For example, a modification to the model that changes the overall dimension of a structural component will result in an automatic update in the arrangement, spacing, and clearance for the reinforcing steel bars. Automatic scheduling of bar lengths and bar quantities and monitoring of bar marks and shapes is supported for several national reinforced concrete design codes and specifications. Geopak exploits the graphical user interface (GUI) capabilities of MicroStation to provide a large range of specialized touch-click-and-drag editing functions to move, copy, or stretch an instance of a reinforcing-bar object. Figure 18.6 and Figure 18.7 show example screens from the Geopak rebar modeling system (Geopak, 1996). **ArtifexPlus** is a rebar and formwork planning software that specializes in complex compound units. Automatic prefabricated generation of completely reinforced structural modules such as staircases and foundations is supported. Reinforcement planning supports the import and export of reinforced areas, thereby enabling complete or partial reuse of reinforcement models for other projects. The mesh-reinforcement program supported by the reinforcement-planning package provides useful routines for laying single meshes or groups of meshes. Detailed

![Figure 18.6 Geopak® rebar modeling.](image)
FIGURE 18.7  Geopak® rebar modeling detail.

FIGURE 18.8  ArtifexPlus application.
FIGURE 18.9 ArtifexPlus application, cross-sectional sketches.
18.4.4.5 Automated Manufacturing of Reinforcement Bars

Concrete construction shows a trend toward integrating the achievements of automated design and construction capabilities, at least in off-site production. One example of this trend is the development of an automated rebar manufacturing machine (Navon et al., 1995). This machine produces bars larger than 16 mm in diameter. The machine receives the raw steel bar in a discrete manner, automatically inputs the bars for processing, cuts and bends the bars, and disposes of the excess material. In addition, the machine deals with the temporary storage of the finished product (see Figure 18.10). The machine was designed and developed with the aid of the ROBCAD graphical simulation system. This made it possible to check, in a three-dimensional environment, the logic of the material flow, the production methodology, relative location of the subsystems, interference between parts of the machine and the product, and the productivity of the process. The developers of this machine claim a 30% higher productivity compared to traditional rebar-bending machines.

18.5 Conclusions and Future Activities

Research and development of core technologies for automated construction equipment continues to make remarkable progress; however, much remains to be accomplished to bring about the successful automation of today's concrete construction and related work tasks. Concerns for short-term profits, fierce competition among contractors, and lack of top management commitment to technological change are often cited as primary obstacles to the rapid introduction of automation and robotics technology among construction firms. To date, the primary motivation for the robotization of on-site work was to remove humans from safety and health hazards. Eventually, with shortages of skilled construction labor becoming more acute, the scope of tasks considered for automation will be enlarged to include the simple, high-volume, and repetitive tasks that could be effectively automated. More emphasis on the development of new construction systems will be put on the redesign of traditional work tasks to better match the limited capabilities of automation and robot technologies. Automation of design and planning of reinforced
concrete structures at A/E/C firms has become, to a large extent, a reality. The most recent developments in the automation of design–construction integration are taking advantage of the existence of the information superhighway, allowing company professionals to communicate and transfer data instantly not only within their own organization, but also to clients, subcontractors, and other parties that may be located worldwide. This trend, independent of on-site work automation, is likely to continue.

References

BSI. 1996. Objective MicroStation, technical abstract. BSI Group, Exton, PA.


The construction of the Allianz Arena, a 70,000-capacity stadium in Munich, Germany, makes a fine example of a multi-crane site. Nearly 20 tower cranes, as well as several mobile cranes, were in use when this photograph was taken in September of 2003. (Photograph courtesy of Israel Mizrahi, Israel.)