Automation and Robotics in Construction X
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Robotics and Automation in the Construction of the Sliding Domes of King Fahd's Extension of the Prophet's Holy Mosque in Madinah, Kingdom of Saudi Arabia

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Abstract
The King Fahd's extension of the Prophet's Holy Mosque in Madinah, Saudi Arabia, is the largest and most complex addition in the Mosque history. One of the most innovative features in this landmark project remains to be the unique twenty seven sliding domes, 18m x 18m each, covering its twenty seven interior open courtyards. With complex geometric and quality requirements, the design and construction of most components and segments of these domes had to rely on computer-driven robots. This paper describes the sliding domes and their major elements, materials and features. It also describes in detail the process used in their production, with emphasis on the role of robotics. The paper elaborates on how the use of robot-intensive industrial processes are utilized in the construction of such a major civil project. The successful completion of these magnificent domes witnesses to the validity and practicality of the use of robotics in the construction industry.

1. INTRODUCTION

Traditionally, the quality of a building comes from its design, the arts and crafts developed over the centuries and the special techniques used in its construction. Industrial production processes have gradually replaced the traditional ways of making objects. Until recently the design and construction processes have oscillated widely between excessive commercialization of ornamentation, typical of late nineteenth century, and its absence in the "modern" movement.

The advent of a wider application of computers and robots in the design and construction of civil projects has ushered a new era into the world of architecture and engineering where these new tools have received increasing attention by both researchers and practitioners around the world [1]. One of their significant contributions is reflected in how they have allowed a very refined development and control of the desired forms that can serve human aspirations and spirit rather than the law of the machine. This is enhanced by the many other advantages of the new applications. It is estimated that computer-integrated design and construction can result in approximately 10 to 15 percent increase in the overall productivity with accompanying significant improvements in cost, safety and quality [2].

On the other hand, robotics in construction have faced numerous challenges, some shared with the industrial processes, that have required extensive research and investment. These challenges have been grouped into three general areas: the development and control of the robot itself; its application into a production process; and the formation and delivery of the final product. In the area of their development and application, robotics have dealt with several significant issues which included the level of programmability, flexibility and intelligence of the robot itself, the scale and size of the product, degree of repetitiveness in the operations, number of product elements, economics of automation, design optimization and the reconciliation of traditional crafts and materials with their modern counterparts [3-5].

The design and construction of the Prophet's Holy Mosque in Madinah utilized numerous sophisticated processes, such as the automated production of artificial stones, marble and granite and other materials. However, the design and construction of the sliding domes remain to be the most innovative feature of this project where computer-controlled robots have been used extensively. Following is a description of the sliding domes and the use of computers and robotics in their design and construction.

2. THE PROPHET'S HOLY MOSQUE AND THE SLIDING DOMES

The Prophet's Holy Mosque in Madinah, the second holiest site in Islam, consists of the existing old part, about 16,500 square meters in area, and the new King Fahd's Extension of 82,000 square meters. The new extension includes twenty seven inner open courtyards, 18m x 18m each, which required a mobile cover that could be opened and closed to control and support the air-conditioned environment of the Mosque. This resulted in the design and construction of twenty seven sliding domes, Figure (1).

Figure 1: Cross-Section of a sliding dome showing the open and closed positions.

The sliding dome consists of a spherical portion and a support frame riding on four steel wheels on steel rails. Each wheel is driven by a direct-drive electric motor with a manual over-ride. The spherical portion of the dome consists of the following elements(Figure 2):

1. A steel structure composed of 24 meridians and 3 ring beams. The structure supports the inner and outer cladding in addition to an internal insulation and waterproofing systems.
2. An inner cladding of wood-laminate reinforced by wood-laminate flanges and supporting the inside intricate decorative elements.
3. An outer cladding of 50 mm hexagonal ceramic tiles glued with epoxy resin to carbonfiber laminate which in turn is reinforced with carbonfibre flanges.

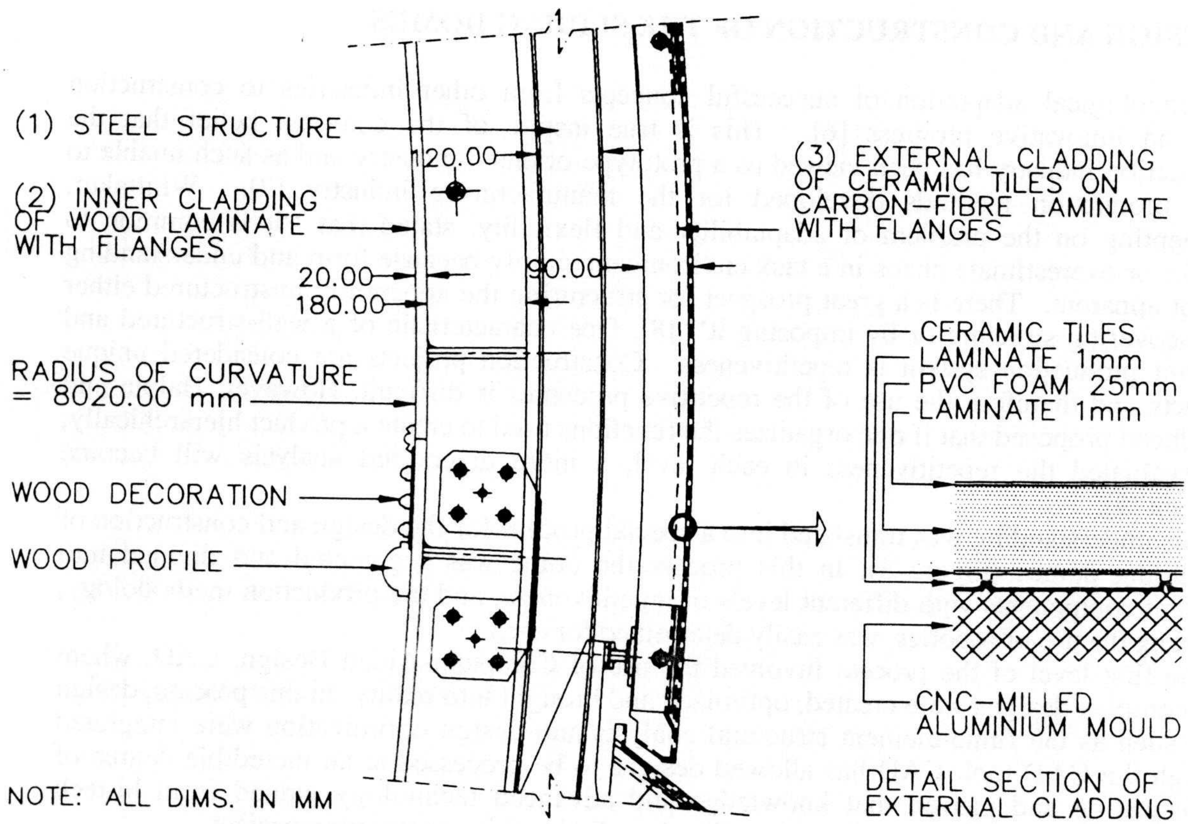

Figure 2: Cross-Section of the Spherical Portion of the Sliding Dome.

3. DESIGN PROCESS OF THE SLIDING DOMES

At the start of the project, initial thoughts were directed to selection of known traditional materials, maximum use of off-the-shelf components and reliance on in-situ construction. The uniqueness of the Mosque and its sliding domes and the demanding aesthetic requirements of Islamic design revealed rapidly that a wide-range evaluation of all possible designs, materials, crafts and technologies was warranted.

The adopted process involved the following steps:

(a) Preliminary designs for all feasible options;
(b) Working scale models;
(c) Review, evaluation and choice of preferred design and materials;
(d) Final design; and
(e) Construction of a full-scale working prototype.

It was through the last two steps that construction methodologies were evaluated and the use of CAD and robotics in the construction of the prototype was decided. Economic analysis of robotic production of critical elements in the prototype predicted equivalent cost to those of traditional methods but with far superior quality and precision. This was an early solid proof that application of robotics to the total project would be economically competitive.

4. DESIGN AND CONSTRUCTION OF THE SLIDING DOMES

Technological adaptation of successful concepts from other industries to construction offers an innovative progress [6]. This is true inspite of the common belief that the construction industry has been viewed as a prototype-oriented industry and as such unable to apply production methods developed for the manufacturing industry [7]. Whittaker, commenting on the problem of adaptability and flexibility, stated that "it is common to mistake or overestimate chaos in a task environment simply because form and understanding are not apparent. There is a great prospect for structuring the apparently unstructured either by discovering structure or by imposing it" [8]. One characteristic of a well-structured and efficient production system is repetitiveness. Construction projects are considered unique products and therefore the use of the repetitive processes is difficult. However, Halpin and Woodhead proposed that if one organizes the functions used to create a product hierarchically, and evaluated the repetitiveness in each level, a more diversified analysis will become apparent [9].

This understanding was translated into a special process for the design and construction of the sliding domes (Figure 3). In this process the dome was segmented and divided into different components with different levels of repetitiveness, and the production methodology, including the use of robotics, was easily determined for each.

The first level of the process involved the use of Computer-Aided Design, CAD, where very complex designs were created, optimized and brought into reality. In this process, design tasks such as the finite-element structural analysis and design optimization were integrated through the CAD tool. CAD has allowed designs to be processed at an incredible degree of sophistication and proved that knowledge and advanced technology gained from hi-tech manufacturing industries could be adapted and applied to this construction project.

The next level involved the direct utilization of Computer-Aided Machining, CAM, in the production process where incredible advantages could be realized (Figure 4). Many forms that could have only been approximated were now made with great precision. Errors, that came from transfer of information from one medium (i.e.design drawing) into another (i.e.shop drawing) were completely avoided. Tolerances could be reduced to minimal ranges and unparalleled high quality standards in technical and artistic details were reached.

The design of the sliding domes was made from the beginning with a three dimensional CAD program on PCs. The spherical shape of the dome dictated the use of a design process that could handle the complex mathematical formulation that described some of the inner and outer decorative components.

The inner cladding was planned to be a composite wood laminate consisting of several layers of wood veneer bonded with epoxy resin. The entire shell was segmented into single

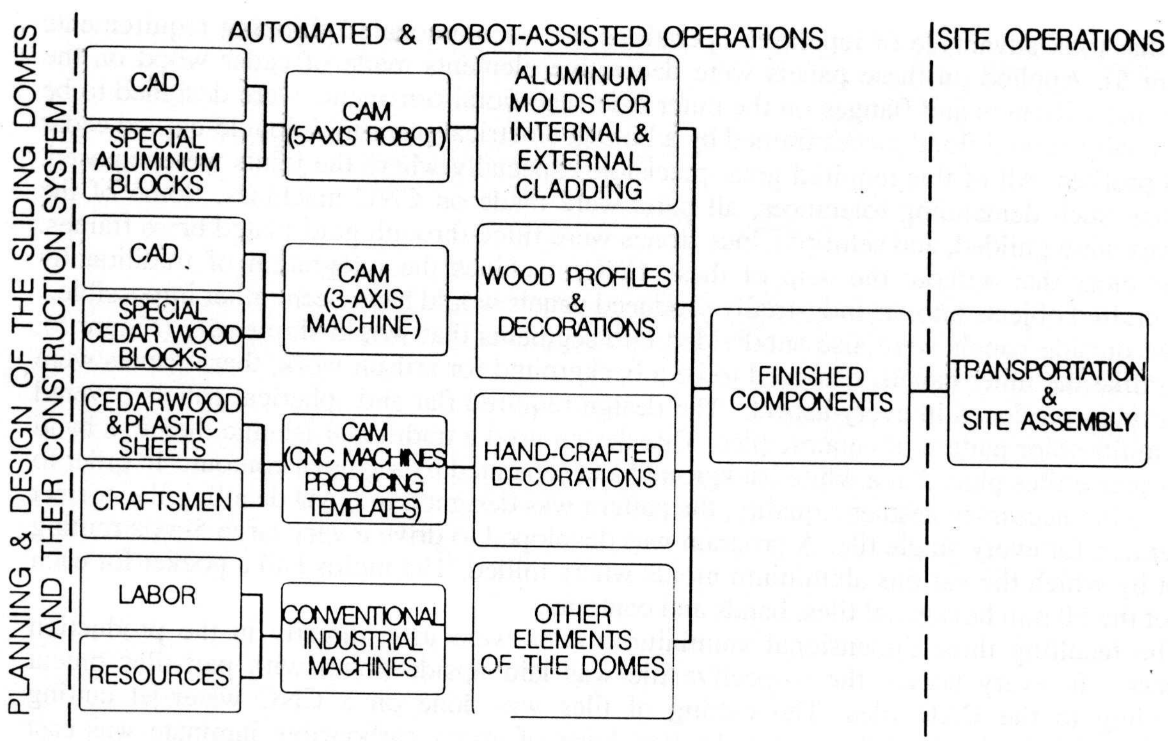

Figure 3: Robotics and Automation in the Design and Construction of the Sliding Domes.

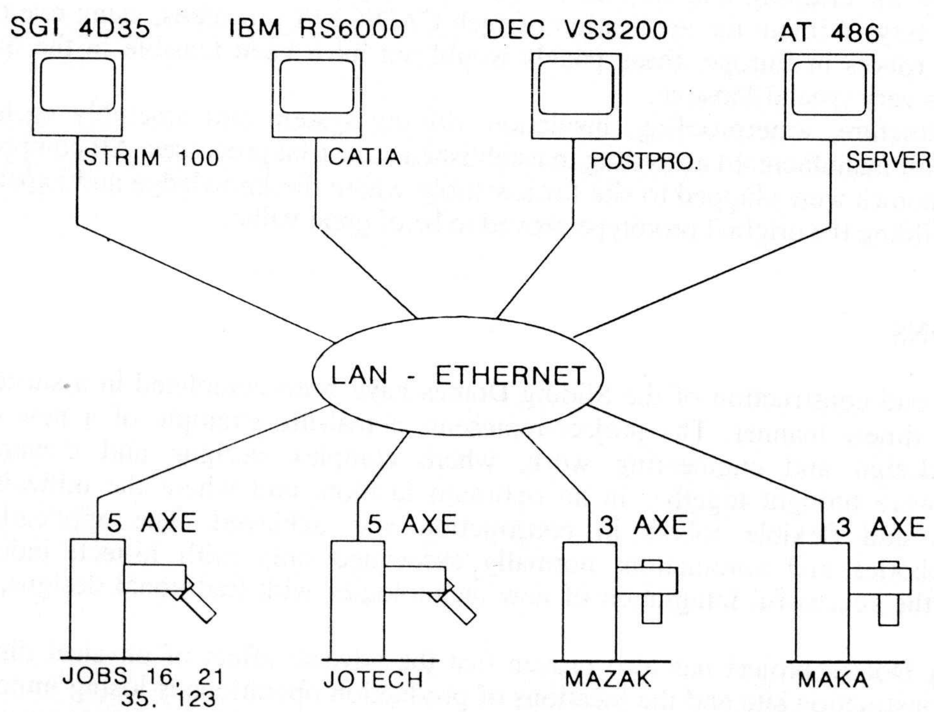

Figure 4: Interaction of CAD and CAM systems in the Sliding Domes Project.

parts that took advantage of repetitive operations and accommodated shipping requirements (Figure 5). Applied on these panels were decorative elements made of cedar wood on the inside and stiffeners and flanges on the outer side. The floral ornaments were designed to be traditionally carved floral pieces framed by a bold geometrical pattern of double-curved cedar wood profiles. All of this required great precision, especially where the joints were exposed. To meet such demanding tolerances, all parts were made on CNC machines. Some of the surfaces were guilded, and semi-precious stones were fitted through gold-plated brass frames. It was clear that without the help of these CNC machines the integration of traditionally hand-crafted objects into the industrially produced panels would have been rather impossible.

The outside panels were also subdivided into segments that would ship easily (Figure 5). But unlike the inner panels, designed to be a background for artisan work, these panels were industrially produced in every aspect. The design required flat and spherical panels covered with multi-color pattern of ceramic tiles. This design used a traditional Islamic theme: a band of turquoise tiles placed in a white background and separated by a golden contour. In order to achieve the necessary aesthetic quality, the pattern was designed in CAD detailing the correct placement for every single tile. A program was developed to drive a very large 5-axis routing robot by which the various aluminium molds where milled. The molds had a pocket for each one of the 50 mm hexagonal tiles, bands and contours.

The resulting three dimensional aluminium molds were used directly in the production process. In every pocket the respective tile was laid upside down with part-tiles precut according to the CAD files. The cutting of tiles was done on a CNC water-jet cutting machine. On the back of these tiles the first layer of epoxy-carbonfibre laminate was cast directly. Then a PVC layer was placed and the final layer of epoxy-carbonfibre laminate was cast to complete the sandwich. The entire package was then covered with a foil and pressed in vacuum under high temperature. After the resin was hardened, the panels were taken out of the molds ready for cleaning and shipment. The resulting panels were of great precision, stability and beauty. Without the application of such CAD/CAM processes, using one of the largest milling robots in Europe, these panels would not have been feasible in the quality required for this very special Mosque.

The steel structure, waterproofing, insulation, driving system and assembly tools and materials were all manufactured according to established industrial processes. All components of the Sliding domes were shipped to site for assembly where the knowledge and experience gained from building the original prototype proved to be of great value.

CONCLUSIONS

The design and construction of the Sliding Domes have been completed in a successful, economic and timely manner. The project represents a real-life example of a new era in architectural design and engineering work, where complex designs and construction requirements were brought together in an optimum fashion, and where the utilization of programmable and flexible robots in construction was achieved. The application of computers, robotics and automation, normally associated only with hi-tech industries, demonstrated the successful integration of new technologies with traditional designs, crafts and materials.

The Sliding Domes project has also proven that the adverse effect of physical distances between the construction site and the locations of production operations is losing importance rapidly. This was demostrated by how resources as well as design and construction processes in four continents were integrated and brought together to build a fitting and functioning part of this magnificant edifice.

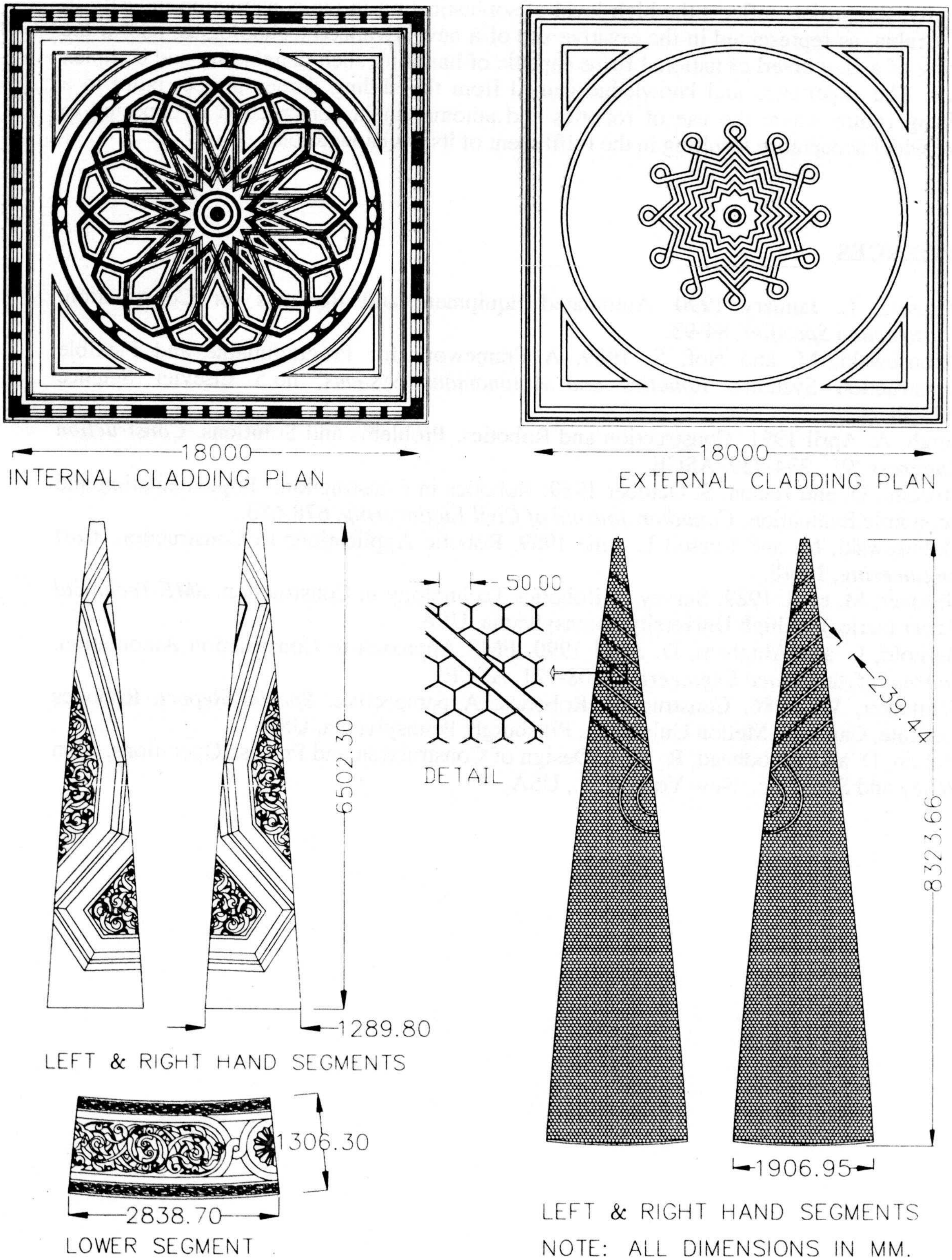

Figure 5: Patterns and Segmentation of Internal and External Cladding of the Sliding Domes.

Finally, the project reflects the high level of sophistication in the construction industry in Saudi Arabia, as represented in the positive use of a new advanced technologies, and in the maturing of a new breed of national firms capable of handling such demanding and complex projects. The experience and knowledge gained from the sliding domes project point to a promising future where the use of robotics and automation in construction is expected to receive wider acceptance resulting in the fulfillment of its envisioned role.

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