NANO-TO-METER-SCALE AUTOMATED BUILDING

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Abstract

Development of nano and biotechnologies encouraged us to develop a concept of automated building, which will significantly reduce the many negative impacts of traditional construction on the environment. The paper describes the concept of Nano- to meter-scale building, a new way of building, which unfolds from the nano into the meter range. The concept is based on bionanorobots, producing building materials using carbon, contained in CO_2 from the air. Criteria and requirements regarding nano and biotechnology are defined and compared to the current research in the field of biotechnology, nanorobotics and production of carbon nanotubes. The paper is further presenting a new building technology that will enable control and monitoring of construction at nano level, as well as requirements regarding design methods and tools, for the digital model of the building will become the only input to the automated nano-building process. The paper concludes with a plan of further research and development.

KEYWORDS: automated building, nanotechnology, biotechnology, Building Information Model (BIM).

INTRODUCTION

Sustainable building processes are one of the essential requirements to return the development of our society into balance with our home planet. Cement industry alone produces about 5% of global man-made CO2 emissions (Worrell et al. 2001), 10% building material and 20-30% construction effort is wasted in USA, and there are vast amounts of other materials (steel, glass) that have to be produced, transported and built in. Although surveys indicate a fairly high level of awareness of and preparedness to implement relevant measures to reduce the negative impacts during the actual construction phase (Son et al. 2009), there is little evidence of radical improvements.

Some new ways of building do, however, promise to significantly reduce the negative environmental impacts. The robotic building system d_shape is based on 3D printing concept (Monolite 2009). The material with a resistance and traction much superior to Portland Cement is produced using any kind of sand and a binder. D_shape products are currently limited to a 6x6m cube. Another attempt of automated production has been developed at University of Southern California's Center for Rapid Automated Fabrication Technologies. Concrete and gypsum are used as the basic material. Strain gauges and other components can be embedded within walls to vary the composition of structures by layering in different materials during construction. Metal reinforcement, plumbing, electrical systems, and tiling can also be automated (Bowen 2007).

Development of the core nano and biotechnologies is leading to results that are extremely interesting for production of buildings on the nano level, growing them on site from the nano into the meter range, without polluting the environment. Although areas like nanorobotics, molecular nanotechnology, programmable materials, and programmable cells are still considered to be speculative to some extent, their fast development encouraged our systematic research of new ways for modelling and construction of buildings using bio-nano-technologies.

The "vision of buildings that build themselves" is not new. It has been often expressed by visionaries, but only as some future technology, for which we have to wait for at least two decades (Zhu et al. 2004). The same authors have also noticed that "nanotechnology R&D in the broad area of construction and the built environment lags behind other industrial sectors". Our motivation to begin with conceptual top-down design of a nanoBuild system before nanotechnology delivers the necessary basic technologies was exactly to accelerate the process. By formulating the requirements we intend to encourage researchers in bio and nanotechnology to direct their bottom-up research towards them. With the interdisciplinary top-down and bottom-up research we want to construct test beds in which we will be able to study the concepts of nanoBuild and develop technologies that will help the construction industry to reach the ultimate goal, the fully automated nano-to-meter-scale building.

THE CONCEPT OF BUILDING FROM NANO TO METER SCALE

A top-down concept has been developed following certain suppositions, which are closely related to our motivation to reduce waste, pollution and energy consumption caused by traditional building technologies. The first supposition therefore was to use materials that exists on site and can be transformed into building materials at the nano level. Since carbon nanotubes have extraordinary characteristics, which can be varied using today's production nanotechnologies, the next supposition, therefore, was to use carbon as the basic material. As carbon exists in nature in vast amounts, the next supposition was to extract it from CO2 from the air. The building process is to be executed on the nano level using active nano devices that shall be controlled extrinsically using a detailed Building information model (BIM) as the source of all necessary information.

The defined suppositions brought us to the following conceptual solution:

1. The fundamental building process is taking part at nano level by multifunctional nanodevices (nanorobots), which are capable of

   a. capturing CO_2 from the air and extracting C molecules from it, releasing O_2 back into the air, and

   b. building 3D carbon nanotube arrays with characteristics required for a specific area (strength, conductivity, color, transparency etc.)

2. Nanorobots are controlled and powered externally by light; instructions are coded using specific wavelengths.

3. Light is emitted by a projector installed above the site. To avoid interference with light emitted by other sources, an adequate wavelength spectrum has to be chosen.

4. The projector is using the detailed BIM model as input, and transmits continuously the horizontal cross-section, going from the bottom to the top height of the model - see Figures 1 and 2.

5. Openings of the final model are temporarily filled with carbon nanomaterial, which transforms back into CO_2 after a specific time period (or under specific conditions), when its function as a supporting structure is fulfilled.

6. All utilities and coatings (if necessary) are built at the same time, together with the bearing structure (e.g. pipelines, power lines, communication lines), and are part of the building.

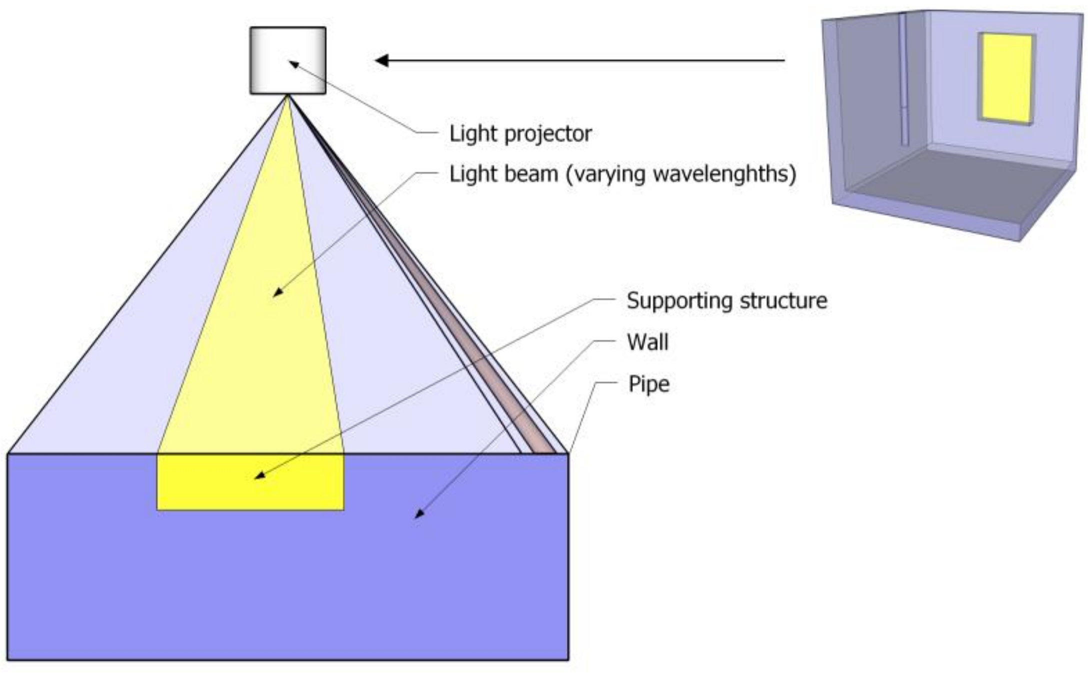

Figure 1: Projection of light-encoded instructions to the nanoproduction layer

The building process consists of the following steps:

1. Designing a detailed BIM model with all necessary utilities and coatings, as well as temporary fillings (these can be added automatically after the building model is

finished by following the rule that every part of the structure has to be vertically supported down to the base level).

2. Site preparation (excavation, projector installation).

3. Deploying nanorobots onto the maximal extent of the building layout.

4. Starting the process by continuously emitting instructions (represented as specific light wavelengths) to build 3D CNT arrays with required characteristics, until the top of the building is reached.

5. After the light is off for a certain time, the nanorobots stop to function permanently, thus preventing any unwanted activity after the process is finished.

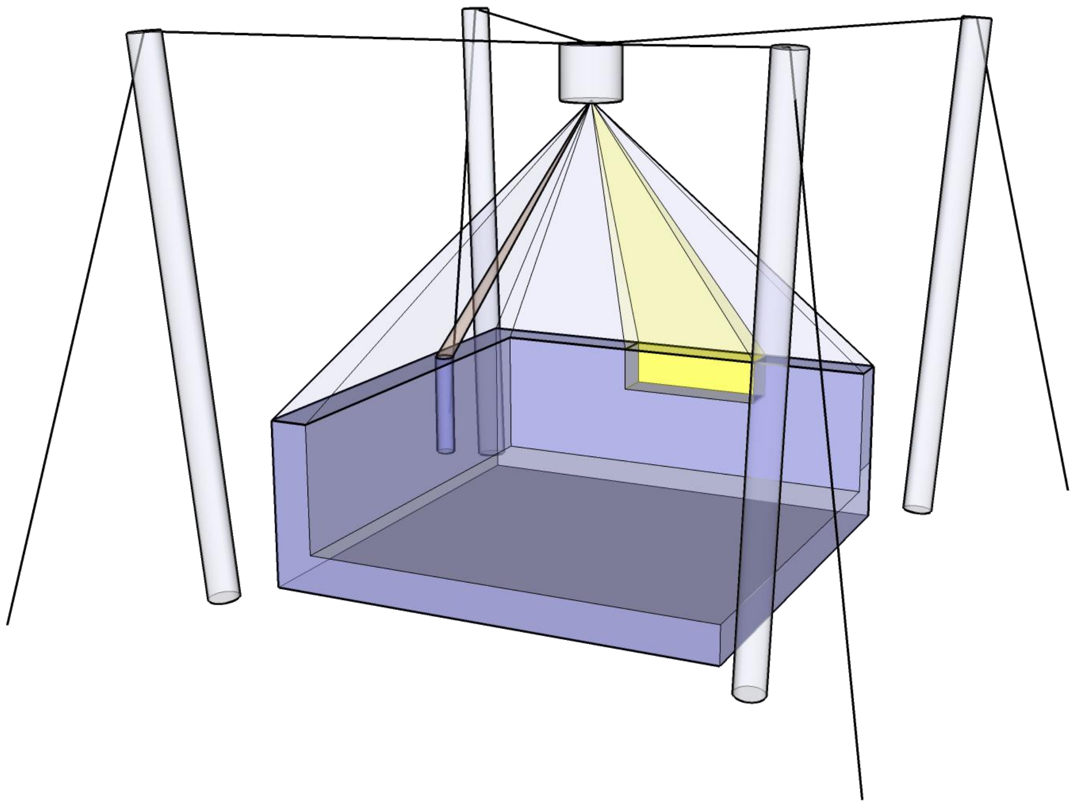

Figure 2: A phase in the nano to meter-scale building process

The load bearing material is in function instantly, therefore the temporary supporting material can dissolve after the building is finished. It disappears off the building in the form of CO_2 gas (e.g. from rooms, niches, pipelines and any other holes). With this the building is finished. With transparent CNTs even windows could be "built-in" during the process, as well as some further equipment. It is, however, too early to explore in such detail all the effects of NanoBuild.

REQUIRED TECHNOLOGIES

From the presented concept we can derive the main required technologies, which today do not yet exist. In this section we will elaborate on each of them in more detail and compare them with existing technologies and opportunities in relevant research areas.

The building material

The widespread use of carbon materials over the past decades has proven their value as a structural material. Recent advances in carbon materials, e.g. Fullerenes (Lau et al. 2002), offer a promise of carbon materials with properties not realized by any other material type. One material of interest to both complement and potentially supersede current carbon fibre materials are atomically precise carbon nanotubes.

Since the discovery of carbon nanotubes in the early 1990s (Iijima 1991) there has been a concerted effort to both characterize and control nanotube properties through careful preparation during synthesis. The predicted properties of atomically precise carbon nanotubes would lend themselves well to a wide range of applications in electronics, thermoelectric and structural materials, and while commercial quantities of defect-free tubes are not yet available, carbon nanotubes are beginning to find use in materials today (Fifield 2007).

The following characteristics are required for the proposed nano to meter scale building process:

1. bearing strength (for bearing of loads)
2. conductivity (for electrical power and communication installations)
3. chemical resistance (for coatings and pipes)
4. color (for coatings)
5. transparency (for lighting)
6. self-decomposition (for decomposition of supporting structures.

Carbon nanotubes possess many of the properties one would choose in designing an ideal structural material. They have a very high strength to weight ratio, are stable and inert at a wide range of temperatures, and can have varying degrees of conductivity based on their geometric properties. However, one challenge in utilizing carbon nanotubes in meter-scale building is finding a natural configuration of nanotubes that allows for unlimited assembly in all three spatial dimensions while retaining the afore mentioned properties.

One very promising family of configurations can be found in Schwarzite structures (Lenosky et al. 1992). The spatial symmetries of Schwarzite structures fulfil the necessary requirement of unlimited assembly in three dimensions. In addition Schwarzite structures are stiff and can be either conductive or insulating depending on their topology (Spadoni et al. 1997). Figure 3 shows a possible nanotube configuration to be used as a nano-scale building block. The tube junctions are Schwarzite structures that have been connected by single wall carbon nanotubes of similar diameter. Dimensions of a single 4 junction cube are 8nm x 8nm x 8nm, its density is 182 Kg/m^3.

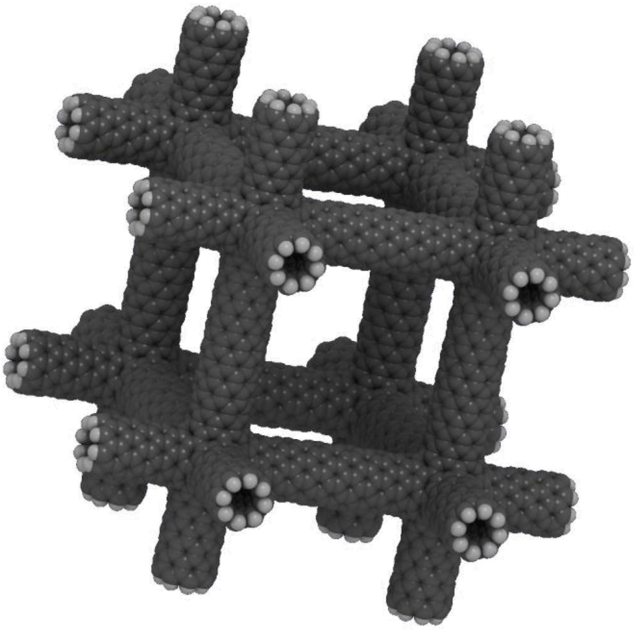

Figure 3: Hydrogen terminated 3D carbon nanotube array

Bionanorobots

The nanorobots are the crucial and the most speculative part of the concept. They have to be able to:

1. recognize different wavelengths and compile them into instructions
2. transform light energy into working energy
3. extract CO_2 molecules from the air and decompose them into C and O_2
4. build 3D CNT array using C molecules

Living cells can fulfil many of the listed activities, therefore biological nanorobots seems to be a possible solution to fulfil the requirements. Biotechnology is already able to modify bacteria to perform in a desired way. Escherichia coli bacterial system has been designed that is switched between different states by red light (Levskaya et al. 2005). Basu et al. (2005) designed a synthetic multicellular system in which genetically engineered 'receiver' cells are programmed to form ring-like patterns of differentiation based on chemical signal that is synthesized by 'sender' cells. Tabor et al. (2009) have genetically encoded edge detection algorithm that programs an isogenic community of E. coli to sense an image of light, communicate to identify the light-dark edges, and visually present the result of the computation. To make multicolour microbes, students from Cambridge University, in England, mined bacterial genomes for pigment-producing genes (Singer 2009). They then engineered those genes into the harmless strain of E. coli, which started to produce desired colours.

Whether and when biotechnology will be able to produce carbon nanotubes is uncertain, but cells are already well able to produce cellulose. Therefore homogenous wood like microbial cellulose could be an intermediate building material produced by bionanorobots in the nanoBuild process.

Building Information Model (BIM) and NanoBuild equipment

In the nanoBuild process the main human activity will be to design a detailed digital model of the building. BIM technology of today, including detailed 3D geometry and material properties, perfectly fits the requirements of nanoBuild. There are, however, some additional demands:

1. in the final model structural elements (walls, columns, beams) have to merge into a single load bearing homogeneous structure, which is to be built in one step

2. all utilities have to be designed together with the architectural elements in final details; they all become solid volumes with specific characteristics (conductivity, transparency, insulation)

3. temporary supporting material has to be filled in all parts of the building, where any part of the structure exist on a higher vertical level (rooms, niches, pipes etc.)

Existing BIM modellers can be extended with special functionality to fulfil these requirements, including the filling of temporary supporting material, which can be generated automatically. Utility design can be supported with parametric functions, which allow input of required characteristics of electrical wiring, water pipelines, etc., with post-processors that create the final detailed geometrical design. The design process will not have to undergo any dramatic changes, except that it will have to be more collaborative and much more accurate. However, small size models could be produced quickly and automatically for review and error checking.

The equipment that is to be used for the nanoBuild process consists of a light projector with a reliable power supply and stable geometrical position, which is crucial for achieving the desired precision of all details of the building. The projector should have a built-in computer that controls the light projection and thus the whole process of nanoBuild. It is connected to another computer on site, which is used to input data (transmit the BIM to the projector) and to monitor the process. No other equipment is required.

CONCLUSIONS

We are aware that the realization of nano-to-meter scale automated building will require many more years of research in the areas of biotechnology (bionanorobots), nanomaterials (3D CNT array), physics (light projector) and construction informatics (detailed and appropriate building information model and modelling tools, building technology system). Intermediate results will probably lead to useful applications (e.g. bionanorobots producing building material based on cellulose), and alternative concepts might arise with different solutions for production of carbon nanomaterial (e.g. self-assembly based nanomanufacturing). This could alter the presented concepts in the future, but not the ecological goals that have been set and which should bring the building industry to a clean and sustainable way of future building. If this paper helps motivate some researchers to focus their work to find solutions for the required technologies, as well as the building industry to believe in the need and the ability to change the building production, then we have achieved our first goal.

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