Robotic application of foam concrete onto bare wall elements

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Abstract –

In the course of frequently altering energy saving regulations, numerous buildings have to be comprehensively refurbished to meet the rising energy-efficiency standards in order to protect the global environment and to save resources. However, available materials as well as adaptable design concepts for additional energy-saving insulation layers are not yet convincing in terms of their long term recyclability nor variation of shape. Therefore, we investigate the application of foam concrete onto bare walls of existing buildings to gain a façade finish which is highly insulating, easily recyclable and at the same time promises to be individually designable due to the properties of the raw material mixture. To ensure controllable as well as reproducible application and to react to changing working methods in architecture and construction, the research focuses on the automatized application of foam concrete using a robotic setup.

We analyzed manual application strategies of foam concrete, considering parameters of handcraft, used tools as well as the reaction on varying material characteristics during application. Based on the analysis results, we present a concept for the robotic application of foam concrete, including suggestions regarding end effectors, robot programming and surface design planning.

Keywords –

Insulation; Foam Concrete; Robotic application; Automated process; Surface Design

1 Introduction

Rising energy efficiency standards and saving regulations increase the number of building refurbishments [1][2]. The constructional implementation of these energy-oriented refurbishment processes mostly include an optimization of the façade's external insulation often executed as External Thermal Insulation Composite Systems (ETICS) in order to reduce internal thermal loss [3]. At the same time, also the recycling standards for construction materials are constantly intensified attaching importance to separability of construction components into varietal raw material to increase reusability of construction material. However, recycling strategies for ETICS most frequently based on expanded polystyrene (EPS) are not fully developed [4]. And due to the high degree of material compound of ETICS, a material extraction with high purity of variety is expected to be only achievable to a minor degree.

To fulfill both mentioned regulations, we introduce the concept of a mono-material thermal insulation system based on an easily reusable as well as highly insulating mineral material. As basis material for this system we investigate the application of foam concrete using different foam concrete densities according to the layers functions. Figure 1 depicts the structure of the system applied to an existing wall including the following layers: anchor with high density of ≤ 800 kg/m³ (a), insulation with low density of ≤ 150 kg/m³ (b), surface finish with low density between 150 and 250 kg/m³ reinforced with specific cement suspension (c).

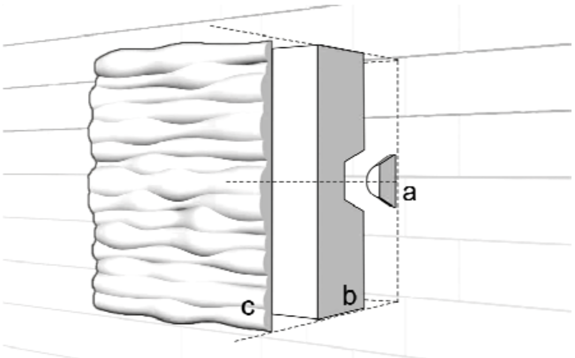

Figure 1. Mono-material insulation system onto bare wall element: anchor (a), insulation (b), designed surface finish (c)

2 Literature Review

2.1 State of the art foam concrete

Foam concrete is proposed as façade insulation layer because it is known for its excellent insulating characteristics due to its low density [5][6]. Furthermore, it is most suitable for façade application because of its higher sound absorbing rate in comparison to dense concrete [7] as well as its acceptable fire resistance [8]. Moreover, foam concrete is ecologically harmless and easily recyclable due to its mineral composition and minimal consumption of aggregate [6][9]. In comparison to similar highly insulating mineral materials such as aerated concrete, foam concrete is strain hardening and therefore also the production process is environmentally friendly due to its low energy consumption [9].

In addition, foam concrete is a competitive material in terms of costs. So far, no reliable study on cost comparison is published. A rough calculation of material costs according to information of local companies indicates a cost saving potential of approximately 15% using foam concrete with a density of 150–200 kg/m³ instead of EPS based systems; even though the layer thickness using foam concrete has to be enlarged to reach the same heat transmission coefficient which EPS provides.

2.2 State of the art foam concrete application

Foam concrete is mainly applied in situ as void fill, bridge abutments and roof insulation or as prefabricated blocks or panels [9][10]. Partly, the blocks are used as insulation material in a constructional setup comparable to external thermal insulation composite systems [11]. While foamed concrete with densities up to 300 kg/m³ is well investigated [6][12] and fabricated as listed above, the manufacturing of building elements made of foam concrete with a low density about 150 kg/m³ is not fully examined nor in common use. However, the lower the density the better foam concrete functions as insulation material due to a decreasing heat transition coefficient [12].

To base the concept of the robotic process on the current foam concrete manufacturing techniques, we analyzed the production process of foam concrete slurry. Mostly, this process consists of the following four sub-steps:

1. Mixing of foam agent and cement slurry separately or mixing of all ingredients at a time
2. Pumping of the foam concrete slurry to its destination of application
3. Pouring of slurry into casting mold or locally predefined in-situ shape
4. Curing

All of these steps but the application via pouring have to be considered for the robotic application concept.

3 Research aim

The overall aim of our research is the development of a concept for the robotic application of foam concrete onto vertical building elements such as bare walls in the context of the explained insulation system. Thereby, the following descriptions are focused only on the outer layer being the designable surface finish of the system.

A particularly robotic instead of manual application is targeted to meet the demands of changing architectural methods and processes not only in the digital design phase but also during the actual building construction and building element fabrication on site. Current trends more frequently establish custom oriented design and adaptable building element generation according to varying structural, physical and aesthetic demands of different parts of one building [14]. In order to be able to feasibly produce and assemble these highly adaptable, parameter based as well as complex formed building elements, the process of building element production has to be generally reconsidered leading to a mass-customized and automated manufacturing process triggering the rapid, affordable and predictable generation of manifold building elements of small batch sizes [14].

However, the commonly used production process of foam concrete via pouring material into molds is not compatible with this development. The great issues thereby are on the one hand the dependency of form generation on the geometric and constructional producibility of the mold and on the other hand the economic competitiveness of small batch sizes using molds which are only reusable to a very limited degree.

Therefore, we investigate suitable application strategies of foam concrete using robotic assistance for direct additive material application without the necessity of expensive or time consuming preparations. Additionally, robots instead of other machines provide the chance of implementing different tools as well as a great variety in path planning throughout different parts of one process [15]. Furthermore, a robotic setup is able to guarantee a reproducible as well as at all times controllable process in comparison to manual application techniques of craftsmen. Using robotic application processes, hence, can lead to a general optimization of the working processes on building sites and an increase in building element accuracy.

4 Research Methodology

The described research started out with an identification of necessary sub-steps for the pursued robotic application concept based on a modification of the described current foam concrete manufacturing techniques (see section 2.2).

1. Material supply including mixing of ingredients as well as pumping of the foam concrete slurry to end effector for application (section 5.1)
2. Development of additive material application technique with focus on generating a flexible method for highly adaptable surface design instead of pouring into casting molds (section 5.2)
3. Curing

In the further course of this interdisciplinary research project our team was focused on the second sub-step of the process. Therefore, the approach as well as the methodology are explained in more detail.

Since this research is related to the outer layer of the foam concrete mono-material system, the distinct and locally adjustable designability of the surface finish within a robotic application process is key factor of the investigation. That is because many factors for this outmost layer greatly vary along the surface area reacting on the different demands of the underlying construction or external circumstances. Some of these factors are exemplary listed below:

- Varying material thickness according to differing thermal insulation demands (especially in the context of refurbishment processes)
- Distinct composition of surface shape for sound insulation of surrounding city noise
- Assurance of rain water discharge
- Aesthetic aspects of architectural design ideas

Harmonizing these aesthetic as well as building physics factors is a highly complex and to a certain extend artistic task of common architectural working methods. Therefore, techniques of the creative industry were used as a research method. Accordingly, manual application experiments were executed enabling an intuitive material handling similar to workflows of sculptors.

In order to find a suitable application technique for the robotic process, the manual application method was used to first, select a tool capable of handling the specific material behaviour and allowing designability during the process. This tool then serves as basis for the development of the end effector. Secondly, the manual application experiments were used to analyse detailed specifications on the path planning parameters of the robotic end effector.

Both experiments were observed not only in terms of the surface designability but as well with the criteria of controllability and reproducibility to gain a fully determinable as well as fully automated process. Furthermore, the analysis of the experiments provides additional information influencing the global robotic setup such as material mixture, processing time, curing progress, order of application, movement speed and direction and amount of applied material.

Based on the experiments and analysis, the robotic application concept was formulated.

5 Experiments

5.1 Material fabrication and supply

The material mixture as well as the material behavior over time greatly influence the application process. In order to provide suitable material conditions, the material fabrication and supply process have to be included in the robotic application concept. In the course of the manual application experiments, we compared two foam concrete manufacturing techniques:

- Preliminary fabrication of foam using a foam branch pipe and mixing of cement slurry plus subsequent folding in of these fractions to gain foam concrete slurry
- Collection of cement ingredients as well as foaming agent in one vessel and afterwards mixing of all fractions at a time with high-performance mixer.

The latter more constantly produced suitable material conditions. Furthermore, this fabrication method had a shorter fabrication time leading to a faster start of application which in turn positively served the materials workability.

5.2 Manual application strategies

The manual experiments were executed using a foam concrete mixture with an approximate density of 200 kg/m³. The underlying vertical wall elements were either made of 4 cm plasterboard or sand-lime bricks. The choice of tools was inspired by the manufacturing techniques of sculptors working with viscous material such as clay. The tools as well as their utilization are listed in Table 1 and further described in the following chapters.

Table 1 Tools for manual application

Utilization	Tools
Spreading	Trowel
Dripping	Spoon
Squirting tubes and drops	Icing bag
Spraying	Spray bottle
Tossing handsize clumps	Hands

5.3 Analysis of application methods

5.3.1 Spraying and tossing method

Experiments with the spray bottle were not carried on because an impeccable material application could not be guaranteed. The concrete ingredients clogged the spraying mechanism. Investigations on tossing were also not carried on because the surface design was not controllable nor reproducible at any time.

5.3.2 Dripping method

Initial tests using the dripping method showed the influence of the relation of applied material amount and speed of tool movement (Figure 2, left).

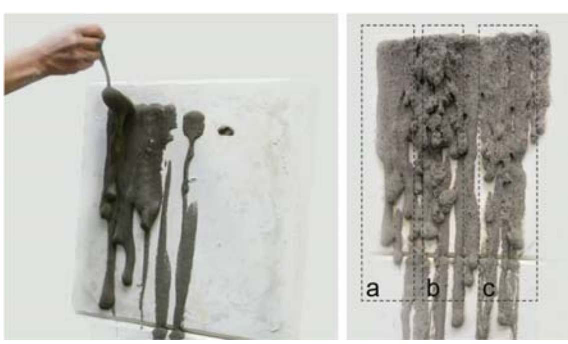

Figure 2. Manual dripping method – application (left) and final result (right)

By quickly dripping the material onto the wall with a volume to contact area ratio of less than 1, the material uncontrollably streams down the wall. This effect increases with a rising fluidity of the foam concrete mixture.

Within the same experiment, the effect of the processing time was observed (Figure 2, right). The depicted foam concrete finish was applied in three time units using the same material mixture. Table 2 displays the observation of the application behavior as well as material quality in relation to the processing time. In summary, the material quality decreases over time due to an increase in foam burst during the storage period. In contrast, the application behavior becomes more controllable over time according to a decrease in fluidity, which is caused by the ongoing curing progress during the storage period.

Table 2 Application behavior and material quality in relation to processing time

Fig.	Time (min)	Application behavior	Foam concrete quality
a	0-4	Strong, smooth streaming	Homogeneous, stable material matrix, good foam distribution
c	4-7	Streaming & fall out of clumps	Inhomogeneous, partly crumbly, foam partly burst
b	7-12	Slight streaming	Inhomogeneous, crumbly, foam mostly burst, material matrix slumped down

Hence, further research has to be focused on the material mixture and additional aggregates to optimize the application process according to curing times and coordinated processing succession.

5.3.3 Spreading method

The application of foam concrete via spreading with a flat, extensive tool represents an advancement of the dripping method. By using the enlarged linear edge of the tool the volume to contact area ratio favorably increases. In this way, an extensive application with a minimum of uncontrollable material streaming becomes increasingly manageable and offers the possibility for the implementation of design strategies such as a wavelike sequence (Figure 3, bottom right) or island like structures with sharp edges and partially smooth surfaces (Figure 3, top right).

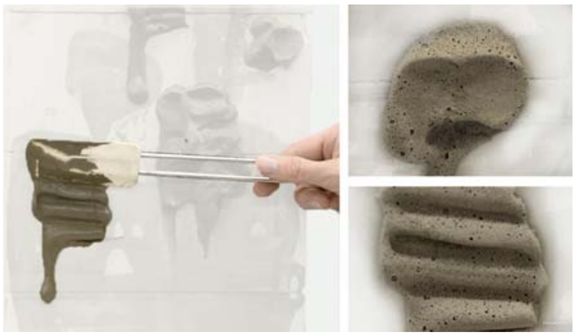

Figure 3. Manual spreading method – application bottom-up (left), final results with smoothed plateau and wave structure (right)

For both methods, dripping as well as spreading, the material supply to the tool ahead of the processing is not yet considered but has to be analyzed and implemented for an automated robotic process.

5.3.4 Squirting method

In contrast to the dripping and spreading method, the results of the squirting method analysis show a higher degree of controllability of the process. The material adhesion to the wall is easily adjustable due to the defined shape and small size of the tool tip as well as the opportunity of adaptable proportioning of material supply. Streaming of the material can be reduced to a minimum by precisely arranging the volume to contact area ratio with this tool (Figure 4, left).

Figure 4. Manual squirting method – application of tubes (left) and final result of drop design (right)

In the course of increasing controllability, the process at the same time guarantees the desired designability of the materials shape. Tube-like and drop-like material application techniques have been successfully tested (Figure 4) which also allow conclusions to be drawn on the path planning for a robot assisted material application (see section 6).

Furthermore, the tools construction of interlinked forming tool and material storage generating a constant material flow provides a conceptual approach for the connection of end-effector to material supply via pipes.

5.4 Conclusion on manual application methods

The analysis shows, that all application methods provide a certain designability with different aesthetic languages of form. In comparison, the squirting method allows for greatest control and reproducibility of form generation during material application of all methods. Moreover, the structure of the squirting tool provides basic connecting factors for the advanced development of a robotic end-effector. Hence, the squirting method is further investigated for robotic foam concrete application and surface design. But since the surface design adjustments are limited to the tool tip size of the squirting mechanism, additionally, the spreading tool is further considered for extensive post-processing of the surface shape without further material supply.

6 Analysis for Path Planning

Suggestions for robot path planning are mostly depending on the tool movement analysis of the different manual application methods. Therefore, additional application experiments were executed for the most suitable methods being spreading and squirting with focus on material behavior according to movement parameters of speed, direction and order.

6.1 Path planning for spreading method

The movement parameters of the trowel for the spreading method had to be investigated more closely in terms of compatibility to the material characteristics. The experiments showed, that material application by spreading performs best when executed bottom-up. By shifting the tool horizontally, unintentional streaming occurs. Whereas top-down movement turned out to be problematic because material adhesion to the tool instead of the wall could not be prevented. As a consequence, the material was dragged along with the tool while only a thin, incalculable layer of foam concrete remained on the wall. In addition, the tilting angle of the tool is important for the spreading method. Any deviation from a parallel position of tool and wall helps to increase material adhesion to the wall instead of tool because of a smaller contact surface area of material and tool.

6.2 Path planning for squirting method

Although the squirting method allows comparatively precise material application anyway, different path orders and directions have been tested. As a result we observed the following path planning factors:

- Linear vertical application works best if performed bottom-up to prevent material drop formation at the end of one application sequence
- For linear horizontal application the speed of the tool movement has to be lower than for the vertical application to prevent minor streaming
- The execution of a combination of horizontal material rows worked best in a bottom-up order. The previously applied row prevents streaming of the following rows and therefore increases shape precision
- For both directions the initial material application has to be executed with a retention time of the tool at the starting position in order to improve material adhesion
- Specific design of the materials shape can be adjusted according to tool speed, distance of tool tip to wall, retention time and force strength of material supply

Moreover, tests on a variation in application order differing from a continuous execution of adjoining rows of material (Figure 5) provide conceptual links for an implementation of curing time in the path planning development, which is expected to increase form precision. The order of application was manipulated to produce every other row of the intended design. With a small time delay, the missing rows were then applied. In the meantime, the curing of the first row set had already proceeded, decreasing the materials high fluidity. This led to a greater form stabilization of these rows and, hence, a decrease in unpredictable material smudging in-between rows was observed.

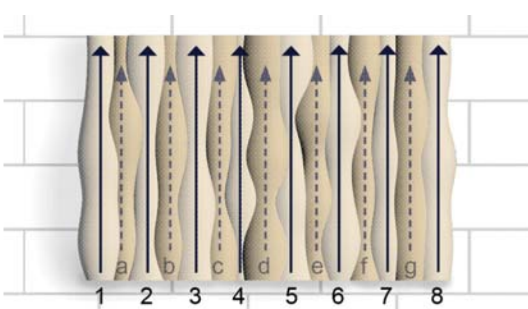

Figure 5. Path order: first material application 1-8, second material application a-g

6.3 Global path planning

The described experiments for path planning analysis were tested in extracts for a material application to cover a surface area of 15 cm x 15 cm. Further research has to investigate the global path planning for entire wall surface areas including a strategy for convenient workflow partitioning and operation order with reference to greatest possible process speed and form precision. Moreover, material characteristics have to be observed to allow smooth transition of material conditions and shape in the course of intended or incidental process interruptions leading to advanced curing progress.

7 Robot assisted application concept

As result of the described experiments we propose the following concept for a robotic application of foam concrete onto bare wall elements, which is also depicted in Figure 6.

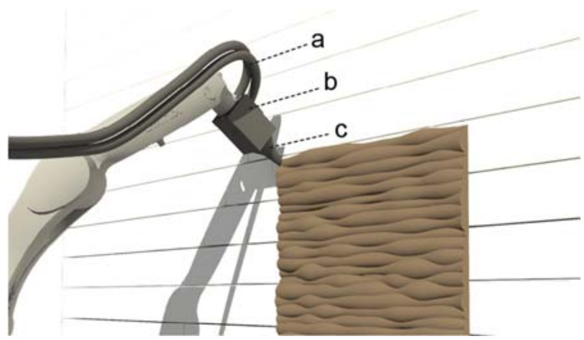

Figure 6. Concept for robot end-effector implementation: (a) separate material supply (b) mixing of material components (c) interchangeable tool tip for varying material shape generation

The concept is based on using a standardized robotic arm with a customized end-effector consisting of the following important elements:

- Separate material supply of foaming agent and cement slurry ingredients via pipes (a)
- High-performance mixing mechanism to produce foam concrete slurry (b)
- Interchangeable tool tip with conical form and varying opening radius for diverse shape generation; directly attached to mixing mechanism (c)
- In addition, a trowel can be attached to the side of the mixing mechanism in order to handle the post-processing of the materials shape with only a slight time delay

The construction of the end-effector elements ensures a fast work progress and a constant material flow from the material supply to the application phase which guarantees best material properties and shape precision of the applied foam concrete.

The suggested process and setup are closely equivalent to 3D printing methods but in contrast to common fields of application of 3D printing, here, a vertical material application is pursued. As part of the ongoing research, the hardware development of this concept can benefit from current 3D concrete printing research. In contrast to the hardware, the robot programming has to be newly developed and implemented because of the modified demands for path-planning of vertical material application as described earlier. Hereby, the main impact for specific application demands is the high fluidity of foam concrete with a low density of about 150 kg/m³ which - if not handled correctly via path planning- leads to unpredictable and uncontrollable material streaming.

8 Conclusion & outlook

The method of analyzing manual application techniques provided a suitable starting point for the development of a robotic concept for the automated application of foam concrete considering a designability of the foam concrete surface shape. The method allowed for intuitive knowledge acquisition concerning the handling of the relatively new material of foam concrete with densities $\leq$ 200kg/m³ as basis for a concept development. The limit of this method was an exact reproducibility of the experiments. Therefore, no quantitative data evaluation was performed.

In the further course of the research project, we are currently developing the hardware and software and verify the conceptual approach.

Figure 7 depicts an initial semi-automated robotic application approach using a modified foam branch pipe. All elements of the conceptual setup considering the end effector are implemented and referenced within the figure (see a-c). This temporary end effector construct is attached to a KUKA iiwa robot and was moved by the manual drive mode instead of a predetermined program. Furthermore, the material supply is achieved via compressed air. At the current state of the ongoing research, material application onto the vertical wall element was in general successful but not yet satisfying in terms of the surface design nor controllability of the process. The influencing factors of the here described research have now to be implemented in more detail to gain the pursued automated robotic application process.

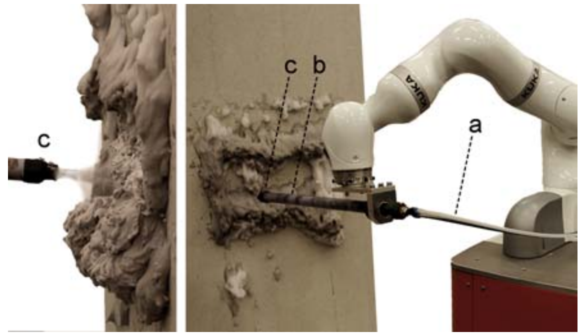

Figure 7. Semi-automated robotic foam concrete application with (a) separate material supply of foam concrete slurry and foaming agent (b) mixing of material components with modified foam branch pipe (c) conical tool tip

Moreover, details of the foam concrete characteristics and manufacturing techniques have to be investigated for improvement of application precision, material adhesion and reproducibility of material properties for constant and consistent material supply.

In order to link the application process to the architectural and constructional working procedures, the robot programming has to be connected to the commonly used software in the field of architecture. Moreover, the concept of using a robotic arm with specific end-effector design has to be extended considering a larger kinematic to allow for material application on the total surface area of a building based on investigations on robotic façade upgrading systems [16]. Therefore, the proposed path planning concept and robotic setup have to be examined for their scalability.

In addition, the application processes for the other layers of the suggested mono-material system have to be developed accordingly.

All in all, we expect a high transferability of the finalized robotic vertical application process for other viscous materials.

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