



International Journal of Engineering, Business and Enterprise Applications (IJEBA)

www.iasir.net

Smart Matter: An Instance of Modifiable Matter for Smart 3D Printing

Pavleen Singh Bali¹, Aditya Jain², Rishabh Aswal³, Gautam Parjapati⁴, J B Patel⁵, Neeraj Gupta⁶

¹B.Tech, Electronics and Communication Engg. (ECE), Amity University Gurgaon, Haryana, India

²B.Tech, Electronics and Communication Engg. (ECE), Amity University Gurgaon, Haryana, India

³B.Tech, Aerospace Engg. (AERO), Amity University Gurgaon, Haryana, India

⁴B.Tech, Mechanical and Automation Engg. (MAE), Amity University Gurgaon, Haryana, India

⁵Prof. Electronics and Communication Engg. (ECE), Amity University Gurgaon, Haryana, India

⁶Asst. Prof. Electronics and Communication Engg. (ECE), Amity University Gurgaon, Haryana, India

Abstract: Smart Matter is an abstract future concept that combines nanoscale robotics and computer science to create individual nanometer - scale computers called Smart Matter atoms, or smart atoms, which can interact with each other to form tangible 3 - D objects that a user can interact with. This idea is more broadly referred to as “**Smart Matter**”. Smart Matter has the potential to greatly affect many areas of daily life, such as telecommunication, human - computer interfaces, and entertainment. Smart Matter refers to an ensemble of individual components, called smart atoms for Smart Matter atoms that can move in three dimensions (in relation to other smart atoms), adhere to other smart atoms to maintain a 3D shape, and compute state information (with possible assistance from other smart atoms in the ensemble). Each Smart atom contains a CPU, an energy store, a network device, a video output device, one or more sensors, a means of locomotion, and a mechanism for adhering to other smart atoms. Programmable matter refers to a technology that will allow one to control and manipulate three - dimensional physical artifacts (similar to how we already control and manipulate two - dimensional images with computer graphics). In other words, programmable matter will allow us to take a (big) step beyond virtual reality, to synthetic reality, an environment in which all the objects in a user's environment (including the ones inserted by the computer) are physically realized. Note that the idea is not to transport objects nor is it to recreate an objects chemical composition, but rather to create a physical artifact that will mimic the shape, movement, visual appearance, sound, and tactile qualities of the original object. The enabling hardware technology behind synthetic reality is Smart Matter, a form of programmable matter that can organize itself into the shape of an object and render its outer surface to match the visual appearance of that object. Smart Matter is made up of individual components, called smart atoms for Smart Matter atoms that can move in three dimensions (in relation to other smart atoms), adhere to other smart atoms to maintain a 3D shape, and compute state information (with possible assistance from other smart atoms in the ensemble). In our preliminary designs, each Smart atom is a self - contained unit with a CPU, an energy store, a network device, a video output device, one or more sensors, a means of locomotion, and a mechanism for adhering to other smart atoms. Smart Matter will be a test - bed for solving some of the most challenging problems we face today: how to build complex, massively distributed dynamic systems. It is also a step towards truly integrating computers into our lives by having them integrated into the very artifacts around us and allowing them to interact with the world. The goal of the Smart Matter is to understand and develop the hardware and software necessary to create programmable matter, a material which can be programmed to form dynamic three dimensional shapes which can interact in the physical world and visually take on an arbitrary appearance. Smart Matter is a technology which can serve as the means of implementing a new communication medium, which we call pario. The idea behind pario is to reproduce moving, physical 3D objects. The power and flexibility that will arise from being able to “program” the world around us should influence every aspect of the human experience.

Keywords: Smart atom, Smart Matter, Synthetic Reality, Pario, MELD, PNA, LDP etc.

I. INTRODUCTION

As reflected in the abstract part, a Smart Matter system forms a shape through the interaction of the individual smart atoms. For example, suppose we wish to synthesize a physical “copy” of a person. Similar to audio and video, we are neither transporting the original phenomena nor recreating an exact replica: instead, the idea is to create a physical artifact that can do a good enough job of reproducing the shape, appearance, motion, etc., of the original object that our senses will accept it as being close enough.

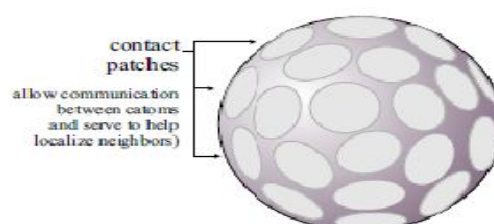


Fig. 1: An Overview of “Smart atom”

The smart atoms [1] would first determine their relative location and orientation. Using that information they would then form a network in a distributed fashion and organize themselves into a hierarchical structure, both to improve locality and to facilitate the planning and coordination tasks. The goal (mimicking a human form) would then be specified abstractly, perhaps as a series of “snapshots” or as a collection of virtual deforming “forces”, and then broadcast to the smart atoms. Compilation of the specification would then provide each Smart atom with a local plan for achieving the desired global shape. At this point, the smart atoms would start to move around each other using forces generated on-board, either magnetically or electrostatically, and adhere to each other using, for example, a nano fibre - adhesive mechanism. Finally, the smart atoms on the surface would display an image; rendering the colour and texture characteristics of the source object. If the source object begins to move, a concise description of the movements would be broadcast allowing the smart atoms to update their positions by moving around each other. The end result is that the system appears to be a single coordinated system. And this is what the idea behind Smart Matter is “Encapsulation” & “Elongation”. The driving force behind programmable matter [2] is the actual hardware that is manipulating itself into whatever form is desired. Smart Matter consists of a collection of individual components called Smart Matter atoms, or smart atoms. In order to be viable, smart atoms need to fit a set of criteria. First, smart atoms need to be able to move in three dimensions relative to each other and be able to adhere to each other to form a three dimensional shape.

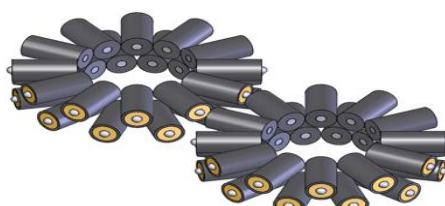


Fig. 2: An Ensemble of various Smart atoms

In the middle section of the term paper the main concept of the topic has been highlighted and various references and examples have been highlighted to give a strong sense of the topic. In the conclusion part of the paper its future application and present efforts have been shown. So, no doubt today only the research part is going on but surely in the coming future it is going to change the world we live in. A Glimpse of what have we achieved in the past and what we are going to create in the coming future.

Where are we in 50 years?

	1949 Eniac	2003 greeting card	2050 Programmable matter
Cost	5M-23M (2002 \$)	1\$	1 millicent
Weight	30 tons	1 oz	20 µg
Volume	450 M ³	1 cm ³	1 nm ³ ?? (1 µm ³)
Power	200KW	20mW	2 attowatts
Cycle time	>200µs	25ns	2 picosec
Storage	<800B	4KB	16KB

Fig. 3: Future Analysis of Technology

II. SCALING AND DESIGN PRINCIPLES

A fundamental requirement of Smart Matter is that the system must scale to very large numbers of interacting smart atoms. In addition to previously stated principles for the design of modular robots we have the following four design principles:

1. Each Smart atom should be *self-contained*, in the sense of possessing everything necessary for performing its own computation, communication, sensing, actuation, locomotion, and adhesion [3].

2. To support efficient routing of power and avoid excessive heat dissipation, *no static power* should be required for adhesion after attachment.
3. The coordination of the smart atoms should be performed via *local control* [4]. In particular, no computation external to the ensemble should be necessary for individual Smart atom execution.
4. For economic viability, manufacturability, and reliability, smart atoms should contain *no moving parts*.

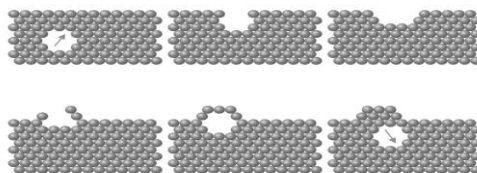


Fig. 4: Hole Motion under local Control

Smart atoms share many of the same features as individual robots in modular (self-reconfigurable) robots (MRR) [5]. In both Smart Matter and MRR the behaviour of interest is group behaviour. The design goals of the individual robots and smart atoms are also similar in that the individuals are self-contained. The differences are however many. MRR are designed to reconfigure their shapes in order to achieve a functionality such as physical movement. While scaling to many robots is a stated goal of MRR, it is not primary since typical goals (e.g., such as moving across a terrain) require relatively few cooperating MRRs. In contrast, the original motivating goal of Smart Matter is to create high-fidelity macro-scale 3D objects from micro-scale components, as reflected in our design principles.

Scaling of Claytronics

	Macro	Micro	Nano
Dimensions	>1 cm	>1 mm	<10 microns
Weight	10's gr	100's mg	<1 mg
power	<2 Watts	10's mW	10's nW
Locomotive mechanism	Programmable magnets Electromagnets	Electrostatics	Aerosol
Adhesion mechanism	Nanofiber adhesives Magnets	Programmable nanofiber adhesives	Molecular surface adhesion and covalent bonds
Manufacturing methods	Conventional manufacturing and assembly	Micro/Nano-fabrication and micro-assembly	Chemically directed self-assembly and fabrication
Resolution	Low	High	High
Cost	\$\$\$ /catom	\$/catom	Millicents /catom

Fig. 5: Statistical Data related to Smart atoms

A. HARDWARE

Even with our design principles, the space of possibilities is enormous. It is helpful to observe, however, that there are several discontinuities in the design space, as summarized in Figure 5 of interest are three regimes: macro, micro, and nano scale smart atoms. At the macro-scale, smart atoms have a diameter > 1cm and weigh many tens of grams. In light of the design principles stated above, the only viable force that can be used to move and adhere smart atoms is magnetic; which sets a lower limit on the size and weight of a Smart atom as the magnets have considerable weight and volume. Furthermore, the circuitry needed for the high currents necessary to switch the magnets increases the weight. At this scale, it may not be possible to adhere to the “no static power” design principle.

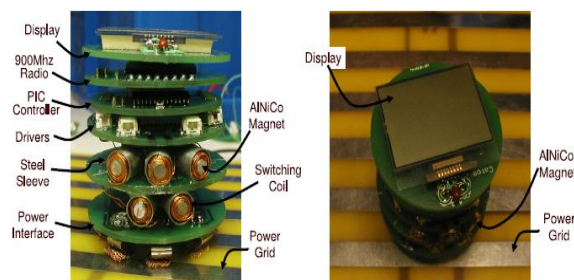


Fig. 6: Structural Overview of a Smart atom

Our current prototype, as shown in Fig 6, is a system composed of smart atoms that only operate in two dimensions. In this case gravity holds the individual smart atoms to a surface and we do not have to deal with the adhesion problem. Much of the weight and size in a macro-scale Smart atom comes from packaging, e.g., chip packages, pins, wires, PCBs, etc. In fact, in our planer prototype currently under construction we estimate that more than 20% of the weight is packaging and more than 77% goes to the magnets and their support circuits.

Micro-scale smart atoms have diameters between 1mm and 1cm and weigh less than 1 gram. Almost all packaging is eliminated and the Smart atom is constructed by bonding VLSI dies directly to MEMS [7] based sensor and actuation dies. The forces necessary to move a Smart atom are now sufficiently small that electrostatic forces become an option. Macro-scale smart atoms would require electric field strengths in excess of the dielectric breakdown of air. *Programmable nanofiber adhesives* (PNA) [8], can be combined with electrostatic actuation to attach smart atoms without using any static power.

III. SOFTWARE

Organizing all of the communication and actions between millions of sub-millimetre scale smart atoms requires development of advanced algorithms and programming languages. The researchers and engineers of Carnegie Mellon-Intel Smart Matter Research Lab launched a wide range of projects to develop the necessary software to facilitate communication between smart atoms. The most important projects are developing new programming languages which work more efficiently for Smart Matter. The goal of a Smart Matter matrix is to dynamically form three dimensional shapes. However, the vast number of smart atoms in this distributed network increases complexity of micro-management of each individual Smart atom. So, each Smart atom must perceive accurate position information and command of cooperation with its neighbours. In this environment, software language for the matrix operation must convey concise statements of high-level commands in order to be universally distributed. Languages to program a matrix require a more abbreviated syntax and style of command than normal programming languages such as C++ and Java.

Similarly, Meld [9] is a declarative language, a logic programming language originally designed for programming overlay networks. By using logic programming, the code for an ensemble of robots can be written from a global perspective, enabling the programmer to concentrate on the overall performance of the Smart Matter matrix rather than writing individual instructions for every one of the thousands to millions of smart atoms in the ensemble. This dramatically simplifies the thought process for programming the movement of a Smart Matter matrix.

```
Void onEmptySpaceReply(Message _msg) {
    if(_msg->getEmptySpace() == -1) {
        //...
    }
    else {
        int empty_space = _msg->getEmptySpace();
        if( hostPointer->getNeighbor(0) != null ) {
            send(hostPointer->getNeighbor(0),empty_space);
        }
    }
}}
```

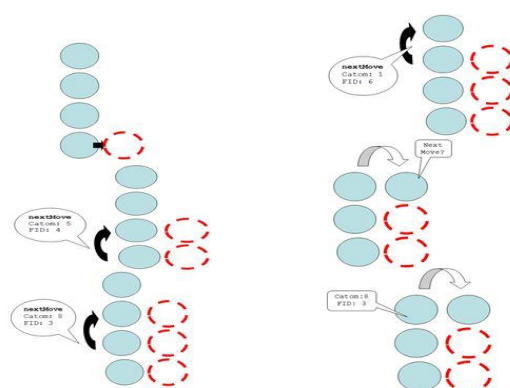


Fig. 7: Working of a Smart atom based on programming

A program that addresses a fixed-size module rather than the entire ensemble allows programmers to operate the Smart Matter matrix more frequently and efficiently. LDP (Locally distributed predicate) [10] further provides a means of matching distributed patterns. It enables the programmer to address a larger set of variables

with Boolean logic, which enables the program to search for larger patterns of activity and behaviour among groups of modules.

A. ALGORITHMS

Two important classes of Smart Matter algorithms are shape sculpting and localization algorithms. The ultimate goal of Smart Matter research is creating dynamic motion in three dimensional poses. All the research on Smart atom motion, collective actuation and hierarchical motion planning require shape sculpting algorithms to convert smart atoms into the necessary structure, which will give structural strength and fluid movement to the dynamic ensemble. Meanwhile, localization algorithms enable smart atoms to localize their positions in an ensemble. A localization algorithm should provide accurate relational knowledge of smart atoms to the whole matrix based on noisy observation in a fully distributed manner.

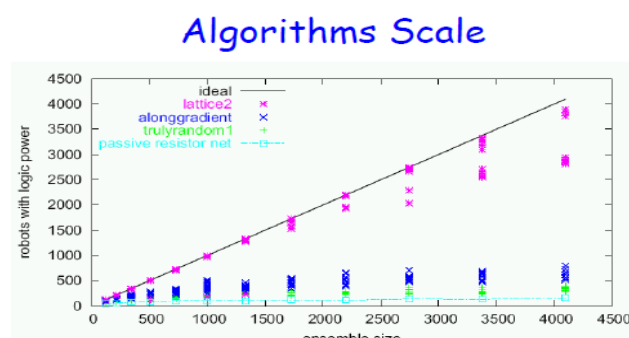


Fig. 8: Algorithms vs. Ensemble size

The essence of Smart Matter—a massively distributed system composed of numerous resource-limited smart atoms—raises significant software issues: specifying functionality, managing concurrency, handling failure robustly, dealing with uncertain information, and controlling resource usage. The software used to control Smart Matter must also scale to millions of smart atoms. Thus, current software engineering practices, even as applied to distributed systems, may not be suitable. We are just beginning to explore the software design principles needed. We have broken down the software issues into three main categories: specification, compilation, and runtime support. Our goal is to specify the global behaviour of the system in a direct and descriptive manner. The simplest model we are investigating with respect to specification is what we call the Wood Sculpting model. In this model, a static goal shape is specified. We are investigating two alternative compilation methodologies, both of which fit into the general category of single-program-multiple data (SPMD) [11] programming models. In the first, we are compiling the specification into a planning problem. In this approach we are inspired by work done in communicating soccer robots and in the context of reconfigurable robots, by the constraint-based control framework in which a high-level description 3 such as a particular gait which is translated to a distributed, constraint-based controller. Our second approach is based on emergent behaviour. Prior work by seems particularly appropriate in this latter approach with respect to Smart Matter.

IV. FUTURE PERSPECTIVE

Millions of these micro robots will be able to emit variable colour and intensity of light, allowing for dynamic physical rendering. The design goal has shifted to creating smart atoms that are simple enough to only function as part of an ensemble, with the ensemble as a whole being capable of higher function. As the smart atoms are scaled down, an on-board battery sufficient to power it will exceed the size of the Smart atom itself, so an alternate energy solution is desired. Research is being done into powering all of the smart atoms in an ensemble, utilizing the Smart atom-to-Smart atom contact as a means of energy transport. One possibility being explored is using a special table with positive and negative electrodes and routing the power internally through the smart atoms, via “virtual wires.” Another major design challenge will be developing a genderless unary connector for the smart atoms in order to keep reconfiguration time at a minimum. Nano fibres provide a possible solution to this challenge. Nano fibres allow for great adhesion on a small scale and allow for minimum power consumption when the smart atoms are at rest.

As the capabilities of computing continue to develop and robotic modules shrink, Smart Matter will become useful in many applications. The featured application of Smart Matter is a new mode of communication. Smart Matter will offer a more realistic sense to communication over long distance called pario. Similar to how audio and video provide aural and visual stimulation, pario provides an aural, visual and physical sensation. A user will be able to hear, see and touch the one communicating with them in a realistic manner. Pario could be used effectively in many professional disciplines from engineering design, education and healthcare to entertainment and leisure activities such as video games. The advancements in nanotechnology and computing necessary for

Smart Matter to become a reality are feasible, but the challenges to overcome are daunting and will require great innovation. 3D Printing would be the much awaited Invention of this Dream Project as it will minimize the Global Market to the proportions of a Village and that to with minimum Time and maximum Accuracy. One likely application for Smart Matter is a 3-D fax machine that would enable the reproduction of three-dimensional objects from transmitted information. While a number of other options have been suggested to achieve this, it is probable that Smart Matter technology would result in much faster reproduction. The object to be reproduced could simply be buried under a layer of smart atoms that would obtain and transmit information about the object's dimensions to a receiving ensemble of smart atoms that would then organize themselves to create an accurate reproduction.

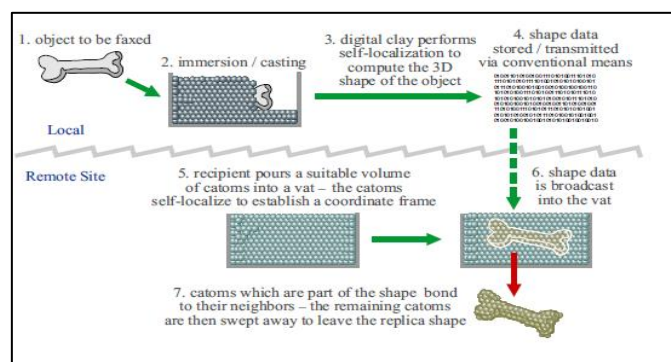


Fig. 9: 3D Faxing and Printing using the basic principles of Smart Matter

V. CONCLUSIONS

Smart Matter is one instance of programmable matter, a system which can be used to realize 3D dynamic objects in the physical world. While our original motivation was to create the technology necessary to realize pario and synthetic reality, it should also serve as the basis for a large scale modular robotic system. At this point we have constructed a planer version of Smart Matter that obeys our design principles. We are using the planer prototype in combination with our simulator to begin the design of 3D Smart Matter which will allow us to experiment with hardware and software solutions that realize full-scale programmable matter, e.g., a system of millions of smart atoms which appear to act as a single entity, in spite of being composed of millions of individually acting units. The power and flexibility that will arise from being able to "program" the world around us should influence every aspect of the human experience. Smart Matter is a technology which can serve as the means of implementing a new communication medium, which we call pario. The idea behind pario is to reproduce moving, physical 3D objects. Similar to audio and video, we are neither transporting the original phenomena nor recreating an exact replica: instead, the idea is to create a physical artifact that can do a good enough job of reproducing the shape, appearance, motion, etc., of the original object that our senses will accept it as being close enough. So surely in the coming future it is going to change the world we live in.

REFERENCES

- [1] Akas, B., Cassel, A., Li, J., Meyyappan, M., & Callen, P. (2007). Friction of Partially Embedded Vertically Aligned Carbon Nanofibers inside Elastomers. *Applied Physics Letters*, 91.
- [2] Ashley-Rollman, M. P., De Rosa, M., Srinivasa, S. S., Pillai, P., Goldstein, S. C., & Campbell, J. D. (2007a). Declarative Programming for Modular Robots. In *Workshop on Self-Reconfigurable Robots/Systems and Applications at IROS '07*.
- [3] Ashley-Rollman, M. P., Goldstein, S. C., Lee, P., Mowry, T. C., & Pillai, P. (2007b). Meld: A Declarative Approach to Programming Ensembles. In *Proceedings of the IEEE International Conference on Intelligent Robots and Systems IROS '07*.
- [5] Byrne, Seamus. (2008, December 22). *Morphing Programmable Gadgets Could Soon Be a Reality*. Retrieved February 20, 2010 from <http://www.news.com.au/morphing-gadgets-could-soon-be-a-reality/story-0-1111118387380>.
- [6] De Rosa, M., Goldstein, S. C., Lee, P., Campbell, J. D. & Pillai, P. (2008) Programming Modular Robots with Locally Distributed Predicates. In *Proceedings of the IEEE International Conference on Robotics and Automation ICRA '08*.
- [7] Goldstein, Seth C. (2010a, January). *Software Research*. Retrieved March 2, 2010 from <http://www.cs.cmu.edu/~SmartMatter/software/index.html>
- [8] Goldstein, Seth C. (2010b, January). *The Smart Matter Team*. Retrieved February 20, 2010 from <http://www.cs.cmu.edu/~SmartMatter/people/index.html>
- [9] Goldstein, S. C., Campbell, J. D., & Mowry, T. C. (2005). Programmable Matter. *Computer*, 38(6), 99-101.
- [10] Goldstein, S. C., Mowry, T. C., Campbell, J. D., Ashley-Rollman, M., De Rosa, M., Funiak, S. et al. (2009). Beyond Audio and Video: Using Smart Matter to Enable Pario. *AI Magazine*, 30(2), 29-45.
- [11] Karagozler, M. E., Goldstein, S. C., & Reid, J. R. (2009). Stress-Driven MEMS Assembly + Electrostatic Forces = 1 mm Diameter Robot. *2009 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2009)*.