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EVOLVING LEGO: PROTOTYPING REQUIREMENTS FOR A CUSTOMIZABLE CONSTRUCTION KIT

Boa, Duncan; Mathias, David; Hicks, Ben
University of Bristol, United Kingdom

Abstract

The PhysiCAD project is a technical feasibility study into the creation of tangible interfaces for Computer Aided Design (CAD) using construction kits. Construction kits, such as LEGO, are a collection of pre-defined physical elements that can be combined using standardised interfaces to produce more complex artefacts. Construction kits like LEGO have a low skill threshold to start using and are highly reconfigurable. The aim of the PhysiCAD project is to merge the benefits of construction kits with CAD. This paper concentrates on one aspect of the PhysiCAD project, how construction kits can be changed to support the representation of physical concepts. To this end we propose the concept of an evolving construction kit with the capability to define and generate new element types within the system. In this paper five requirements for an evolving construction kit are identified along with technical solutions for implementing them. Examples of some of the technical solutions are included along with a discussion about how they could be used to generate new evolved construction kit elements.

Keywords: Construction kits, Early design phases, 3D printing, New product development

Contact:
Duncan Boa
University of Bristol
Department of Mechanical Engineering
United Kingdom
dr.boa@bristol.ac.uk

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1 INTRODUCTION

The PhysiCAD project is a technical feasibility study into the creation of tangible interfaces for Computer Aided Design (CAD) using construction kits. Construction kits, such as LEGO, are a collection of pre-defined physical elements that can be combined using standardised interfaces to produce more complex artefacts. Construction kits like LEGO have a low skill threshold to start using and are highly reconfigurable. The aim of the PhysiCAD project is to merge the benefits of construction kits with CAD, where we consider CAD in its widest sense as a set of digital design tools, not just solid modelers e.g. Autodesk Inventor. The resulting tangible interfaces for CAD have the potential to enable wider engagement of individuals in the design process (Berglund & Grimheden, 2011) and assist users in rapidly representing and testing physical aspects of their designs, such as ergonomics and limits and fits.

Requirements for the physical representation of a concept change over the course of the design process. During ideation and concept generation representations tend to be more ambiguous as they describe concepts that have yet to be fully constrained. As the design process progresses, and the concept becomes more developed, the need to represent concepts in higher physical fidelity increases. Construction kits, such as LEGO, lend themselves to the initial concept stages where their abstract form and necessity for using one's imagination are seen as positives. However, the usefulness of construction kits for physical representation diminishes as a concept is developed and the need for higher physical representational fidelity increases. This is because the physical limitations of construction kits, such as discrete placement (stud patterns), prohibit exact representation between a designer's conceptual intent and the physical prototype.

This paper concentrates on one aspect of the PhysiCAD project, how construction kits can be changed to support the representation of physical concepts. To this end we propose the concept of an evolving construction kit with the capability to define and generate new element types within the system. Over generations of the construction kit, users would end up with a set of customised elements for their specific design needs which have greater capability in physically representing their concept. These elements might have increased functional abilities, such as pivots and hinges, or different material properties, such as texture and flexibility. An evolving construction kit is intended to mirror the iterative process of creating prototypes where individuals move from ambiguous, low fidelity representations (sketching, junk models) to high-fidelity "looks like" and "works like" prototypes.

In this paper five requirements for an evolving construction kit are identified along with technical solutions for implementing them. Examples of some of the technical solutions are included along with a discussion about how they could be used to generate new evolved construction kit elements.

2 CONSTRUCTION KITS

LEGO is by far the most widely used construction kit. Consequentially, it is used as the primary construction kit for developing tangible CAD interface in the PhysiCAD project and as the basis for an evolving construction kit. LEGO, however, has several limitations when used for physical prototyping, such as its rigid adherence to orthogonal assembly and a finite number of element (brick) types. We start this section with a review of LEGO as a construction kit for prototyping. We specifically consider the barriers to LEGO being used to generate high fidelity representations. Following this, we review hybrid physical-digital construction kits and how they can be used in the design process. From the review we present a series of requirements for an evolving construction kit capable of producing high-fidelity physical representations i.e. "looks like" and "works like" prototypes.

2.1 LEGO construction kits for prototyping: advantages and limitations

The variety and quantity of elements within LEGO construction kits has increased substantially since its initial introduction. The current count of unique elements stands at over 5,000 and are available in a wide variety of colours. In this section we appraise the value of LEGO's ability to realise physical representations in the design process.

2.1.1 Advantages of LEGO as a physical prototyping tool

- **Low skill threshold to use:**

The low skill threshold for LEGO is two-fold and concerns model construction and model design. Model construction is simplified by LEGO’s interlocking stud mechanism, which only permits connection of elements in a very limited number of ways. Additionally, the required force and dexterity to connect elements is low, enabling even small children to use LEGO.

The skill required to design commercial LEGO models and sets is high, however, the accompanying instructions act as inspiration for users to design their own models as well as training them in the design rules of LEGO. It is important to highlight that the skill threshold *to start* using LEGO is low but that there is broad scope for increasing this skill and producing more complex designs.

- **Interchangeability and reconfigurability:**

Interchangeability describes the compatibility of LEGO elements with one another. LEGO elements have high interchangeability because of their standardised connection mechanisms and sizes. Variant LEGO elements can readily be substituted with one another and because of this interchangeability, one model can be readily *reconfigured* into another model by changing its layout or adding/subtracting elements. The *reconfigurability* of LEGO is further increased in that two people can easily place the same element in exactly the same place, which is much harder with freeform modelling materials such as clay.

- **Engaging:**

LEGO is primarily intended as a toy to entertain people and because of this playfulness it can be used to encourage participation in a wide variety of activities. Examples of LEGO’s playfulness to engage individuals include: LEGO Mindstorms for robotics education, LEGO Architecture for building design, LEGO Technic for exploring mechanisms, and LEGO Serious Play to enhance innovation and business performance (LEGO, 2016). One of the PhysiCAD tenets is that this playfulness can be used for wider stakeholder engagement and participation in the design process.

- **Assembly speed:**

Creating LEGO models can often be quicker than other physical prototyping methods when accounting for skill levels and manufacturing time. This has already been taken advantage of within the Brickify project, where 3D solid models are analysed to determine which aspects of a component can be substituted with LEGO elements, rather than relying on 3D printing for the entire form (Mueller et al. 2014).

- **Dynamic elements:**

A few basic LEGO elements and the majority of LEGO Technic elements enable dynamic models to be created. Simple mechanisms employing gears, shafts, and links, can be used to quickly produce proof of principle concepts.

2.1.2 Limitations of LEGO as a physical prototyping tool

- **Fixed scaled:**

LEGO’s interconnecting stud mechanism fixes the positional resolution at 8mm. Techniques exist for “bending” this scale rule, however, they impact significantly on the interchangeability of elements.

The scale of models that can be produced with LEGO is also heavily influenced by the use of specialised elements, such as car wheels. As soon as these are used in a model, the scale of the rest of the model is largely fixed to that of the specialised element.

- **Orthogonal construction planes:**

Due to the placement of studs and their counterpart sockets on opposite sides, LEGO elements can generally only be assembled in one direction. Further to this, the intrinsic shape of LEGO elements adheres to a strict planar grid which is strongly biased to constructing models in one direction. Consequentially, more organic shapes and swept surfaces are difficult to reproduce in high fidelity with LEGO elements and can therefore only be approximated. LEGO Technic facilitates multi-plane construction, however, employing this within a model limits the ability to inter-connect elements built in different orientations within the same model.

- **Single material elements:**

LEGO elements are primarily made from a single material. This means that the construction kit has the potential to represent form and structure but other important physical properties of a prototype cannot be included in the model. Inherent to the advantages of physical prototyping are the ability to include these properties within a model, such as mass, stiffness, and texture.

- **Limited dynamic behaviours:**

LEGO Technic elements allow for the modelling of gear and link mechanisms. However, other dynamic behaviour cannot be as readily modelled because physical properties of LEGO elements and their scale are limited. For example, spring shock absorbers are a type of LEGO Technic element but to produce a mass/spring damper system that is specific for a function, the mass, spring stiffness and geometry must all be tuned for the use.

- **High skill requirements for complex models:**

The skill threshold for LEGO is low, however, the highest fidelity LEGO models with the most advanced functionality require significant time and expertise to develop. Designing with construction kits may be more intuitive than other representation and prototyping techniques but it still requires training to master.

- **Finite number of specialist element types:**

To increase the functionality and fidelity of LEGO models a large number of specialised elements exist, such as doors, windows and wheels. As users increase the fidelity of their models, the requirement for specialised elements increases, however the range of sizes of these elements is limited. The alternative is to approximate desired model features with standard LEGO elements, often resulting in lower fidelity representations.

2.1.3 Summary

LEGO as a construction kit has several benefits as a means to physically represent design concepts (Table 1). However, these advantages are highly dependent on the stage of the design process in which LEGO is being used and the concept being represented. At present, LEGO’s advantages lend its use toward the earlier stages of the design process where the need to accurately represent concepts is lower. As concepts mature in their development, the use and ability of LEGO to represent them diminishes. LEGO’s ability to engage individuals in the design process, along with its interchangeability and reconfigureability, are seen as distinct strengths for a physical prototyping tool. These strengths warrant the development of a compatible construction kit system capable of higher fidelity representations.

Table 1. Advantages and disadvantages of LEGO as a construction kit

Advantages	Disadvantages
Low skill threshold to use	Fixed scale
Interchangeability and reconfigurability	Orthogonal construction planes
Engaging	Single material elements
Assembly speed	Limited dynamic behaviour
Dynamic elements	High skill requirements for complex models
	Finite number of specialist element types

2.2 Tangible interfaces for CAD

Hybrid physical-digital construction kits have been used as tangible interfaces for CAD for several applications, including, rapid prototyping electronic user interfaces (Hartmann et al., 2006), constructing architectural models (Eng, Camarata, Do, & Gross, 2006), and robotics education (Schweikardt & Gross, 2006). In these examples the use of a tangible interface for CAD simplifies the process of constructing and interacting with virtual models and systems, enabling non-experts to engage in the design process. In this section a selection of these tangible interfaces for CAD are reviewed with a specific focus on hybrid construction kits. The aim of this review is to highlight successful strategies for hybrid prototyping that can be integrated into an evolving construction kit.

2.2.1 Manipulating symbolic interactions

The Triangles system (Corbet & Orth, 1997) is an early example of a hybrid physical-digital construction kit and consists of a set of identical equilateral triangles with electro-mechanical connectors. Each triangle element in the construction kit can communicate with a computer about its connection to other elements. Of significance is that Corbet and Orth assign symbolic meanings to each of the triangles so that when users manipulate their physical structure they control an animation sequence. Corbet and Orth argue that interacting with a physical structure to explore symbolic interactions makes it easier for users to understand abstract digital information. However, the number of triangles utilised and the length of the animation sequence are limited in their example. With a larger number of elements employed users may struggle to understand the relationship between physical manipulations of the triangle's structure and their corresponding symbolic interactions. This issue could be assisted with bi-directionality between the physical and digital environments.

2.2.2 Progressive complexity

Tangible Interfaces for CAD aim to make the process of designing easier and more accessible to non-experts. However, simplicity of design tools can come at the expense of precision in realising a user's design intent. roBlocks (Schweikardt & Gross, 2006) and d.tools (Hartmann et al., 2006) address this by defining levels of interaction for their systems.

d.tools is an integrated design, test and analysis environment for developing electronic interfaces for a variety of applications, such as a portable media player. In the d.tools system users initially create flow diagrams to describe the behaviour of their electronic interface. At the next level the users assemble physical component from a construction kit including buttons, displays and sensors, which embody the flow diagram from the previous level. In the last level users can edit and customise pre-defined behaviours for construction kit elements to tailor their design to better meet their intent.

Similarily to d.tools, roBlocks, an educational robotic construction kit, has varying levels of interaction complexity. It consists of a number of identically sized cubes that can be snapped together to create basic robots. The first system level is for novice users and initiates predefined block behaviours when two or more blocks are connected. In the second level a communication block links a user's robot with a computer enabling remote control and programming of their creation. Level three lets users define specific actions for blocks in their system and create more complex conditional behaviours.

Progressively enabling the sophistication of these construction kits and systems allows users to heuristically develop an understanding of their capabilities. This balances the need to include sophisticated tools for later stages of the design process without sacrificing a low-skill threshold at the beginning.

2.2.3 Intuitive design modalities

Keyboards, mice, and WIMP (windows, icons, menus, pointers) GUIs (graphical user interface) are not intuitive modalities for 3D design. Proto-TAI (Piya & Ramani, 2014) addresses this with a system for generating 2D shapes from a user's sketches and assembling them virtually in 3D. The system works by using physical planar proxies whose orientation is detected by a Kinect 3D camera. The user orientates the planar proxy, a piece of card, until its corresponding virtual part is correctly aligned in the computer design environment. This aspect of the Proto-TAI system employs what can be considered an intuitive modality for design. However, the more challenging aspect of the system is the formation of a 3D object from 2D sketches. Users must convert a 3D concept of an object into constituent 2D elements, a difficult task.

It is important for a tangible interface for CAD to include intuitive modalities for all aspects of the designing. This is especially true for the generation of 3D geometry, which is presently highly non-intuitive with traditional CAD solid modellers.

2.2.4 Adaptable forms

FlexM (Eng et al., 2006) is a hybrid construction kit made up of struts and hubs. However, unlike other strut and hub construction kits that are rigid once assembled (e.g. K'nex), FlexM has hubs with flexible strut positions. This enables a much wider range of forms to be constructed as an assembled structure can be twisted and sheared to create higher fidelity representations. With a finite number of elements in a construction kit flexibility significantly increases the number of forms that can be represented.

2.3 Summary

Tangible interfaces for CAD aim to make the process of designing easier by employing input modalities that are more intuitive. However, as with all tools even the most intuitive require initial training. Systems that can adapt to user experience and concept fidelity by varying the toolset's sophistication are essential. Tangible interfaces should also be used for more than just inputting physical geometry. Their use as a means to explore symbolic aspects of a prototype may assist greatly with the "fuzzy front-end" of design. Finally, using a construction kit for a tangible interface for CAD is playful. This is one of the key strengths of using kits such as LEGO, as they offer the potential to engage and enthuse individuals in the design process. This playfulness needs to be maintained and if possible, enhanced, in the creation of an evolving construction kit.

3 REQUIREMENTS FOR AN EVOLVING CONSTRUCTION KIT

Prototyping is difficult and time consuming to do effectively. Using LEGO to prototype has several advantages (Table 1), however, as a concept's development progresses the suitability of LEGO as a prototyping tool diminishes. It is the premise of this paper that an evolving physical-digital construction kit based on customised LEGO elements can address these issues. In this section key requirements for such an evolving physical-digital construction kit are outlined based on the advantages of LEGO and hybrid construction kits.

3.1 Symbolic information capture

The initial stages of concept development require designers to articulate and represent ideas that are not yet fully formed. Designers must also structure the design space by listing requirements and constraints related to the concept at this stage. An evolving construction kit should facilitate exploration of this ambiguous design phase by including a mechanism for assigning symbolic meaning to elements such as in the Triangles system (Corbet & Orth, 1997).

3.2 Discrete to continuous

Representing the physical form of a concept with LEGO will always be an approximation. This is because the representation is constrained to the scale of LEGO elements and their positional resolution (which is determined by their stud placement). LEGO operates on a discrete scale and for it to be used to represent a wider range of concepts it needs to be able to transition to a continuous scale.

3.3 Surfaces and curves

Related closely to the issue of discrete placement resolution is LEGO's inability to represent curves and surfaces accurately. LEGO can approximate surfaces and curves using standard bricks but the results require imagination on behalf of the viewer. There are also specialised LEGO elements that are curved, or include surfaces, but these are extremely limited in number and variety. An evolving construction kit should be able to define any curve or surface to represent the full range of conceivable concepts a user may require.

3.4 Dynamic and multi-functional elements

LEGO and other construction kits are primarily concerned with creating structures. LEGO goes further than most other construction kits in including a variety of dynamic and functional elements, such as wheels and gears. However, the total number of these elements is limited in variety and capability (i.e. non-load-bearing). A requirement for an evolving construction kit is the ability to define and generate new dynamic and multi-functional elements.

3.5 Multi-plane construction

LEGO elements are generally assembled one on top of another, with some specialised elements that allow perpendicular connections. This limits the variety of models that can be constructed with LEGO, as well as the resulting models functionality (load bearing capability is greatest for bricks in compression). Multi-planar construction of LEGO elements will increase the fidelity of physical prototypes that can be constructed.

3.6 Requirements for an evolving construction kit summary

An underlying assumption in this section is that interchangeability and reconfigureability of LEGO will be maintained in any evolving construction kit. This is a key concept of construction kits, in that simple elements can be combined with one another to create more complex artefacts. In practical terms for the evolving construction kit this is likely to mean that elements will be combined together using a common interface mechanism(s).

4 METHODS FOR DEFINING AND GENERATING CUSTOMISED LEGO CONSTRUCTION KITS

In this section methods for generating customised elements in an intuitive manner are proposed. The methods are described in relation to how a customised LEGO construction kit could be generated but many would also be appropriate for other types of tangible CAD interfaces.

4.1 Symbolic information capture with RFID tagging of elements

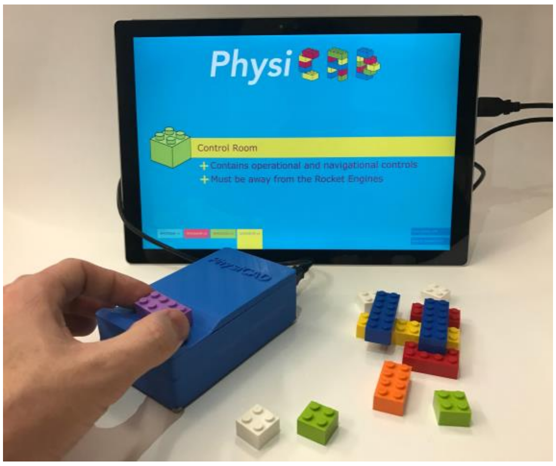

Figure 1. InstructiBlocks, a PhysiCAD system using RFID to embed design rules in LEGO bricks

Radio Frequency Identification (RFID) tags are sufficiently small, and passively powered, that they can be embedded inside individual LEGO elements (as small as a 1x1 brick). The RFID tag could be used to assign a unique identifier to an element which can then be queried using an electronic reader. When the element is queried by a hybrid construction kit system, information which corresponds to that element can be captured or displayed. Information could include design rules, desired material properties, rationale, or any other design information. The InstructiBlocks system in Figure 1 is a PhysiCAD technology demonstrator and explores how design rules can be embedded in individual LEGO bricks to affect design variation of simple models (Bennett et al. 2017, Mathias et al. 2017**)**.

4.2 Discrete to continuous prototyping by scaling and resizing elements

Resizing LEGO elements can be used to move from a discrete to a continuous element scale providing that a consistent interface (stud interval) is maintained. Scaling and resizing will impact on LEGOs interchangeability and reconfigureability but steps can be taken to limit this. Including the original scale of LEGO on resized elements through a visible marking could assist users in this matter.

In a corresponding digital environment of a hybrid construction kit the scale of LEGO elements can be adapted more readily. In this example the physical scale of LEGO bricks can be left unaltered and only their virtual counterparts need be changed. However, the extent to which scale between a virtual and physical model can be distorted and user understanding of both systems be maintained is not clear. This remains an active line of investigation for the PhysiCAD project.

4.3 Surfaces and curves with flexible and deformable elements

Surfaces and curves in a physical prototype can be created with LEGO using flexible and deformable elements. Flexible elements can be produced from elastomeric materials to allow them to bend, or flexible connectors can be produced to connect existing LEGO elements. Examples of flexible elements include FlexO (FlexO, 2016) and bionicTOYS (Pasternak, 2016), both of which are designed to be compatible with LEGO (Figure 2). Embedding strain gauges and flex sensors within these elements could be used as means to detect their form so their virtual counterparts can mirror their shape.

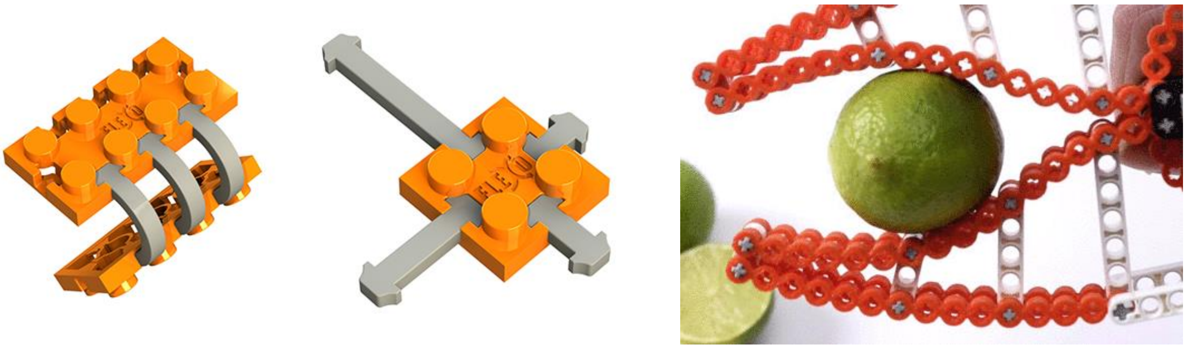

Figure 2. Flexible LEGO connectors and elements (FlexO left, bionicTOYS right)

Producing LEGO elements using deformable materials, such as foam, could also be used to create curves and surfaces in physical prototypes. Users could physically remove material from individual elements to create high fidelity prototypes. A disadvantage of this approach is the irreversibility of it, breaking the major advantage of construction kits which is their interchangeability and reconfigureability.

4.4 Dynamics and multi-functional elements using construction motion

Inertial Measurement Units (IMU) generate accurate data about their orientation in up to 9 degrees of freedom (DOF) using magnetometers, gyroscopes, and accelerometers (Figure 3 right). The Bosch BNO055 IMU samples at 100Hz and can measure acceleration to 1 milli-g and angular velocity to milli-degrees-per-second. The sensor measures 2.5x2.5mm (excluding power supply and breakout board) and is small enough to be embedded within a 1x1 LEGO brick.

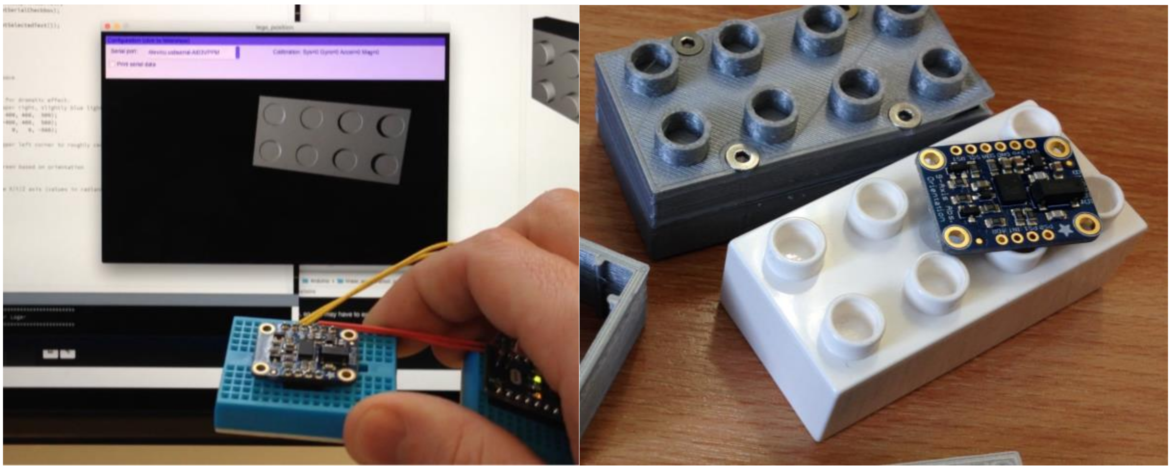

Figure 3. (Left): a BNO055 orientation sensor controlling the orientation of a virtual LEGO brick. (Right): a BNO055 orientation sensor breakout board in relation to a DUPLO brick.

Understanding and knowing the orientation and motion of a LEGO brick can be used to localise bricks within an assembly and to define dynamic elements (Figure 3 left). In several examples of hybrid construction kits hand gestures are used to generate 3D profiles by tracking a user’s hand movements as they sweep an imagined surface. The same process could be used in an evolving construction kit to define dynamic elements. Users would instruct the system that two elements are related and through relative motion between the elements define a dynamic motion. In this example simple hinges and pivots could be produced.

4.5 Multi-plane construction with adaptors and orientation detection

Multi-plane assembly with LEGO can be accomplished with specialised adaptors that permit the construction of LEGO elements in non-orthogonal angles. These might take the form of ball and socket joint connectors or flexible elements that can be plastically repositioned. Embedded orientation sensors in elements can also be used in conjunction with temporary adhesives (such as blu-tac). A user could stick LEGO elements to each other in the planes that they desire. The embedded orientation sensors would then capture the relative angles between the elements and allow the system to produce a new element based on this.

4.6 3D printing and multi-materials

The previous sections describe methods for defining new LEGO elements for an evolving construction kit. As a design progresses and the user increases the fidelity of their physical representation the new evolved LEGO elements will need to be created and introduced. Additive manufacturing is proposed as the principal method for creating the new elements, as the process can be highly automated and is flexible in geometric forms that can be produced. Additive manufacturing methods such as fused deposition modelling (FDM) are low cost and capable of producing multi-material parts at very high quality. Pick and place machines could be used in conjunction with this to add functionality to evolved elements by combining standard parts, such as motors, with them.

5 CONCLUSIONS

Physical prototyping is advantageous in many situations as it is more intuitive and enables wider engagement with non-experts. Physical prototyping also helps to embody aspects of a design, such as mass, fits, and feel, that are difficult to communicate with digital only modelling. Digital modelling has a high degree of flexibility in the forms that can be represented and has sophisticated simulation capabilities to analyse a design. The PhysiCAD project aims to merge the benefits of these two paradigms with a hybrid physical digital construction kit consisting of LEGO and twinned digital models.

Challenges in implementing a hybrid construction kit surround the capabilities of LEGO in creating high-fidelity physical representations. It is proposed that an evolving hybrid construction kit based on LEGO elements is a solution to this problem. The evolution of the construction kit elements would mirror the process of prototyping, where users start with abstract and ambiguous concepts (standard LEGO elements) and add detail to them over iterations (evolved LEGO elements). In parallel to the physical modelling process a twinned digital model of the prototype would be automatically created. The digital model would inform the creation of evolved LEGO elements as well as providing digital affordances, such as version control and sharing.

In this paper a number of advantages and disadvantages are described relating to LEGO as a construction kit. The disadvantages of LEGO are to be addressed by supplementing it as a construction kit with evolved elements. Users would define their own evolved elements in the process of prototyping so that they meet their specific design requirements. A number of methods, including the use of construction motion and resizing elements, are proposed as methods for users defining the evolved elements. The principle challenge in achieving this concerns the capturing of the physical model’s structure and generating a digital model from this. Localisation, mapping and scanning techniques for doing this include computer vision approaches and instrumented bricks. At present, the practical resolution of these techniques is in the order of magnitude of 5 – 10mm, insufficient for a reliable and consistent user experience or accurate digital models.

Additional challenges for an evolving construction kit relate to the use of additive manufacturing for the generation of new elements. Currently, a 2x4 LEGO brick takes around 15 minutes to print at standard quality. Larger and more complex evolved elements are likely to take significantly longer. A distinct advantage of prototyping with construction kits is the ability to iterate quickly. This in turn lowers the cost of discovering problems earlier in the design process and increases design thinking (Hartmann et al., 2006). Until additive manufacturing techniques are able to produce components at a rate in the order of seconds, the interruption to design thinking could be too much. Large-scale parallel printing could act as a stopgap until advances in additive manufacturing enable the required production speeds.

The concept of an evolving construction kit offers a novel approach to physical prototyping. However, the nature of evolving LEGO elements may serve to reduce the inherent advantages of the construction kit over successive generations i.e. its interchangeability and reconfigureability. The PhysiCAD project aims to answer these questions and work continues to develop technology and design demonstrators to assist in this.

REFERENCES

Bennett, P., Boa, D., Hicks, B., & Fraser, M. (2017). “InstructiBlocks: Designing with Ambiguous Physical-Digital Models”. *11th International Conference on Tangible, Embedded and Embodied Interactions*. Yokohama, Japan.

Berglund, A., & Grimheden, M. (2011). “The importance of prototyping for education in product innovation engineering”. In *ICORD 11: Proceedings of the 3rd International Conference on Research into Design Engineering, Bangalore, India, 10.-12.01. 2011*.

Corbet, M. G., & Orth, M. (1997, August). “Triangles: Design of a physical/digital construction kit”. In *Proceedings of the 2nd conference on Designing interactive systems: processes, practices, methods, and techniques* (pp. 125-128). ACM.

Eng, M., Camarata, K., Do, E. Y. L., & Gross, M. D. (2006). “Flexm: Designing a physical construction kit for 3d modeling”. *International Journal of Architectural Computing*, *4*(2), 27-47.

Stolten, J. (2016). *Flexo -Bendable, bouncy, flexible building bricks!*. *Indiegogo*. Retrieved 10 June 2016, from https://www.indiegogo.com/projects/flexo-bendable-bouncy-flexible-building-bricks#/

Hartmann, B., Klemmer, S. R., Bernstein, M., Abdulla, L., Burr, B., Robinson-Mosher, A., & Gee, J. (2006, October). “Reflective physical prototyping through integrated design, test, and analysis”. In *Proceedings of the 19th annual ACM symposium on User interface software and technology* (pp. 299-308). ACM.

LEGO.com Serious Play Home. (2016). *Lego.com*. Retrieved 20 December 2016, from https://www.lego.com/en-gb/seriousplay

Mathias, D., Boa, D., Hicks, B., Snider, C., Bennett, P., & Taylor, C. (2017). “Design Variation through Richness of Rules Embedded in LEGO Bricks”. *21st International Conference on Engineering Design*. Vancouver, Canada.

Mueller, S., Mohr, T., Guenther, K., Frohnhofen, J., & Baudisch, P. (2014, April). “faBrickation: fast 3D printing of functional objects by integrating construction kit building blocks”. In *Proceedings of the 32nd annual ACM conference on Human factors in computing systems* (pp. 3827-3834). ACM.

Pasternak, M. (2016). *bionicTOYS | Flexible building bricks for new LEGO® play*. *Kickstarter*. Retrieved 10 June 2016, from https://www.kickstarter.com/projects/1229300248/bionictoys-because-nature-is-flexible

Piya, C., & Ramani, K. (2014, August). “Proto-tai: Quick design prototyping using tangible assisted interfaces”. In *ASME 2014 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference* (pp. V01AT02A097-V01AT02A097). American Society of Mechanical Engineers.

Schweikardt, E., & Gross, M. D. (2006, November). “roBlocks: a robotic construction kit for mathematics and science education”. In *Proceedings of the 8th international conference on Multimodal interfaces* (pp. 72-75). ACM.