Democratizing Design Through the Use of Lego-Inspired Universal Connectors

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Abstract— Students at Penn State University are working on the design of an affordable and sustainable Innovation Space where people from various walks of life can converge to rapidly prototype innovative products that meet their unique needs and preferences. This Innovation Space is being designed for resource-constrained contexts like East Africa where unemployment rates exceed 40% and systemic challenges impact people's lives and livelihoods. This space provides innovators a vehicle to rapidly and effectively take ideas from a concept to a product. A key feature of this space is access to various kinds of connectors and structural elements that collectively form a full-scale "Lego set" for innovators. Universal connectors made of mild steel form the vertices of structures with the edges made of locally-available materials like mild steel, plastic or bamboo. Special connectors have been designed to add wheels to structures or make bicycle-powered devices. This paper presents the conceptual framework for this connector-centric prototyping environment and showcases some of the products that can be prototyped there. The overarching objective of this venture is to develop a Lego-inspired set of connectors that forms the nucleus of innovation spaces to be implemented in secondary and vocational schools in East Africa. We envision that these Innovation Spaces will nurture small enterprises based on the connectors themselves as well as market-driven products designed with them. More importantly, it will provide the next generation of students a venue to develop their creativity, design skills and an entrepreneurial mindset.

Index Terms—Design, Prototyping, Innovation, East Africa, Universal Connectors

I. INTRODUCTION

Entrepreneurship is the engine and driving force of an economy. Entrepreneurship is directly associated with job creation, innovation, economic growth and development. Unfortunately, until the 1990s, the importance of entrepreneurship was undervalued and consequently downplayed in Africa [1]. However, since then, the study of entrepreneurship and indigenous private enterprise has become a significant component of research on economic development in Africa [2, 3]. Development experts agree that the culture of entrepreneurship must be grown in these countries and cultures from the ground-up. Schools are the most appropriate forums to inject entrepreneurial zeal into the system. Schools can provide support structures that channel entrepreneurial energy into the communities and support early-stage ventures. Science and technology education can catalyze economies and enable them to leapfrog sub-optimal approaches to addressing social challenges. The concurrent growth of the agrarian and knowledge economy can be accelerated by educating youth to leverage science and technology for income generation as well as long-term value creation [4]. Developing entrepreneurial mindsets and capitalizing on human ingenuity are essential to help communities and economies advance from sustenance to sustainability [5].

The African continent has a population of around one billion people, half of which are children, and of these, 50 million are orphaned or abandoned. 54% of the African population is under the age of 20 and poverty rates are over 50% [6]. Rapidly decreasing fertility rates in most western nations and steady birth rates in developing countries have led to a "youth bulge" in several countries across sub-Saharan Africa and the Middle East [7]. These young people are vulnerable to extreme poverty, disease, exploitation and crime but also have the capacity to be a phenomenal resource for growth. The potential of such disenfranchised and disillusioned youth must be harnessed to meet the twin goals of economic growth and poverty alleviation. Developing innovation and entrepreneurship competencies amongst these youth is a critical first step in the journey towards long-term sustainable development. This is particularly important because a small fraction of the students that complete high school will be accepted into Bachelor’s degree programs. The rest of the students will join the millions of students who completed or dropped out from secondary school and are attempting to find local employment, migrating to the cities in search of petty jobs and joining the cadres of the unemployed or underemployed. Some youth will engage in petty trade but lack an entrepreneurial mindset, focusing on short-term subsistence rather than long-term growth and value-creation. In essence,
II. Jua Kalis: Enterprising Metalworkers

Urbanization around the world has pushed the boundaries of major cities at an alarming rate in recent decades. As development programs like the United Nations Millennium Development Goals (MDG) seek to end extreme poverty globally by 2015, major solutions must focus on the rapidly expanding urban areas. In nations such as Kenya, in the midst of ballooning slums, the unemployment rate has remained largely stagnant at 40% in the last decade [10]. This is a clear indication of the great chasm that exists between rising populations and the need for development in urban marginalized communities. How do the people in these communities eke out a living? It is estimated that 72% of the labor force in Kenya depends on the informal sector for their livelihoods and empowering this demographic is critical for macro socio-economic development [11]. In Kenya, approximately 1.3 million micro-enterprises employ over 2.4 million people, and the Jua Kalis account for 19% of the GDP [12]. Jua Kali means ‘hot sun’ and refers to enterprising craftsmen that work all day to make products from metal, wood, plastic and other materials. A few hundred thousand of these individuals work in hundreds of workshops that have sprung up on the outskirts of cities and in rural areas. Their products range from agricultural implements to home furniture to automobile parts; anything and everything that will be consumed by the local communities.

While the Jua Kalis are generally skilled at their specific craft, like other East African entrepreneurs, they have built up a notorious reputation for being unprepared, uninspired, and lacking creativity in designing new products [13]. Nearly all products purchased by East Africans are either imported or knock-off versions made by the local informal players like Jua Kalis [14, 15]. There is little emphasis on indigenous design to solve local problems due to a lack of trust in locally produced goods [15]. Heavy reliance on foreign technologies has inhibited the development of a local culture of design and innovation [15, 16]. In essence, product design activities are focused on the detailed design and manufacturing phases [17]. Across the formal and informal sectors, design activities related to need definition and conceptual user-centered design are extremely limited. The fear of damaging manufacturing tools and machines limits tinkering, and the high cost of imports discourages design and prototyping of new products [15]. The Innovation Space seeks to address the fundamental challenge of designing novel products that meet the four hallmarks of sustainability – they are technologically appropriate, environmentally benign, socially acceptable and economically sustainable. The Innovation Space focuses on early-stage prototyping and design thinking with due attention given to the business strategy and implementation strategy.
Even simple technologies cannot survive in the marketplace without sound business models, which in turn depend on entrepreneurial networks [16]. There is wide consensus on the importance of developing innovators in schools and creating linkages between the academic and business worlds [16]. In schools, engineering fundamentals must be supported by activities that continually translate between practical and abstract concepts [18]. Informal economy workers can serve as excellent liaisons between the schools and the business world. Students can be empowered by allowing them to prototype their ideas with basic building blocks [4, 19]. These building blocks allow students to turn their designs into working prototypes that can be ultimately commercialized on a larger-scale by the Jua Kalis [16, 20]. We envision the universal connectors described in this paper as the basic building blocks to catalyze the design of innovative products.

III. UNIVERSAL CONNECTORS

The inspiration for universal connectors comes from a similar project undertaken by a faculty-student team at the San Jose State University. This team, led by Prof. Leslie Speer, developed a set of steel connectors that can easily be used to fabricate carts, backpacks and dollies [20]. Our team was inspired by the work at SJSU and started exploring the connector concept afresh in Tanzania. Design goals for our team included the simplification and strengthening of the connectors and the development of a family of connectors that can collectively be used to prototype diverse products. Initial research showed the simplest connectors to fabricate consisted of orthogonal angles with various geometries of mild steel sold at local hardware stores. In many structures, the connections are generally the weakest points. Strengthening the connections is often a reliable way to improve the lifespan of a product. The cost, availability, fabrication methods, and physical properties are important parameters for choosing connector materials [21]. The material of choice for us was mild steel as it is the most economical, accessible and easiest to work with.

In order to develop a standardized canonical set of universal connectors, just like Lego sets or Erector kits, we studied many different types of connectors. Preliminary research in Tanzania experimented with using the connector

Fig 1. Commonly found connectors in the human body and products around us.
concept as a prototyping tool. Strips of inner tire tubes were used to tie down bamboo poles to the legs of the initial connectors to create edges of chairs and tables. The idea of temporary connectors fueled the research team to map out all the different ways objects are connected. Figure 1 shows a connector map that includes permanent and non-permanent fixtures that are used by many products. Typically, permanent connections consist of adhesives that render the members inseparable without causing damage. Epoxy, wood glue, and polyvinyl chloride (PVC) cement are some of the common adhesives used to fix objects together. The primary drawback to using adhesives in resource-poor settings is their high cost and lack of reusability. Minimizing or finding alternative ways to design products without adhesives is advantageous. Non-permanent connections such as threads, pins, and basic geometry are an ideal way to design connectors. In regards to prototyping, non-permanent connectors are the most useful due to their modular and independent nature [22].

While developing the connector map, two fundamental questions emerged: 1) what are the set of connectors that are truly universal and 2) how will these connectors function without needing additional supplies? Typical connectors sold at local hardware stores have 90° angles and are used for gas, water or sewage lines. The standard coupler, elbow, and tee-connectors used to build piping systems in buildings have been used for generations. In exploring the limits of orthogonal connectors, we determined that there are a total of eight configurations that are feasible and necessary (Figure 2). Further, within the orthogonal connector family, the connectors can have at least three different types of cross-sections: hollow pipe-like, solid, and semi-circular (Figure 3).

Solid connectors made of square or cylindrical steel bars are generally the easiest to fabricate due to their wide availability and ease of welding. For example, the connectors in Figure 5 are mild steel rebar connectors that provide the foundation for the skeletal structure of our low-cost greenhouses. These connectors are used with connecting edges made of polypropylene random copolymer type 3 (PPR) pipes. Open connectors, like those with an “L” shaped cross-section (Figure 6), are often more expensive but are easy to cut and weld. They are particularly well-suited for prototyping since they can be connected to the edges easily using strings, tire strips, or wires. Drilling holes through them is also relatively easy.

When utilized as a prototyping tool, the connectors either form the vertices of structures or connect various materials or functional parts. For example, the chair frame (Fig. 7) is made up of 16 nodes. The universal connectors, which form the vertices of the structure, are connected to each other by rods that are made of metal, plastic, wood, bamboo or other locally-available materials. If needed, clamps can be used to prevent motion in the Cartesian directions. The connectors can have a circular, rectangular or right-angled cross-section. The kind of connecting rods (edges) that are easily available should be considered when determining the kind of connectors. The connectors shown in Figures 2 and 3 have a circular cross-section while the connector shown in Figure 4 has a hollow square cross-section. Rebar, circular metal pipes or PVC pipes fit perfectly into these square connectors making it easier to build structures.
fabricate and hence they have not been included in the current set. Rather than using curved connectors, curved edges made from plastic tubing can be used for prototyping very effectively. In essence, the goal of the connector sets is to provide structural support and let other materials such as connector rods, rice bags, cloth, wooden wheels and tubing bring innovative concepts to life.

IV. Universal Connector-Based Prototypes

Designing a chair was the first application of the universal connectors (Fig. 7). A chair can also be as simple as a stool made of one 6-way connector (Fig. 8). The number of connectors needed is contingent upon the degree of robustness desired in the product and the kind of edges available. The model of the chair (Fig 7a) uses hollow circular orthogonal connectors. The prototype chair (Fig 7b) uses two three-way and two four-way “L” shaped connectors. The legs of the chair (edges) are made of wood, PVC, aluminum and mild steel. Notches are made on the connectors and the legs are fastened using metal wire. Rice bags are used for the seat and back support and simply nailed to the wooden frame. The chair itself can be used as a component of a wheelchair, exemplifying the modular approach to design.

![Chair made with one six-way connector](Fig 8)

An inexpensive wheelchair (Figure 9) was designed using hollow connectors, recycled rice bags and bicycle wheels. Bolted clamps are used to prevent motion in the Cartesian directions and keep the frame together. The modular nature of the design allows the structure to be readily assembled as the individual pieces are held together by the geometry and not by adhesives. For instance, the chair portion of the wheelchair is simply bolted onto the top of the frame. The wheels on either sides are kept in place by a solid shaft, which tapers off to fit into the wheel hub and is pinned in place to prevent sliding. The front side of the wheel has a third wheel connector that is a castor wheel fixture. The user can replace the chair with a basket and replace the castor wheel with two front wheels to convert the wheelchair into a cart. The frame is designed to allow users to add attachments that provide additional value to the users. For example, a corn-sheller can be fixed to the frame and allows users to shell corn (a major staple food) for family consumption or to sell in the local markets and augment income.

![Wheelchair made with Universal Connectors](Fig 9)

V. Conclusion

Over the course of the last two years, several Universal Connectors have been designed, prototyped and field-tested in the US and Tanzania. The application of the connectors for low-cost greenhouses is a prime example of the practical relevance of this approach to prototyping and manufacturing. While designing and building the chair and wheelchair using the connector concept, we have determined
the pros and cons of different connectors and better understand the kinds of objects that can be prototyped with them. We are also conducting rigorous testing on the connectors to assess their structural strength. In the Spring 2012 semester, we challenged 32 teams of freshmen engineering students to develop designs for more advanced connectors that connect structures with bicycles, carts or other objects. Several interesting designs emerged from these teams and we are developing a few of the concepts further. Our team will be conducting a series of 32 half-day design-build sessions and focus groups in Kenya in Summer 2012. We will be engaging secondary school/college students and Jua Kali workers in urban as well as rural areas to understand how they approach this connector-centric design-build process and document the kind of innovations they come up with. We will also be assessing the feasibility of setting up a pilot Innovation Space at one of the two educational institutions that we have been working with over the last few years. The outcomes of field-testing in Kenya in Summer 2012 will lead us to the design of the next generation of Universal Connectors and an implementation strategy for the Innovation Spaces in rural as well as urban schools in Kenya.

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