Exploring Physical Prototyping Techniques for Functional Devices using .NET Gadgeteer

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ABSTRACT
In this paper we present a number of different physical construction techniques for prototyping functional electronic devices. Some of these approaches are already well established whilst others are more novel; our aim is to briefly summarize some of the main categories and to illustrate them with real examples. Whilst a number of different tools exist for building working device prototypes, for consistency the examples we present here are all built using the Microsoft .NET Gadgeteer platform. Although this naturally constrains the scope of this study, it also facilitates a basic comparison of the different techniques. Our ultimate aim is to enable others in the field to learn from our experiences and the techniques we present.

Author Keywords
Physical construction, form-factor, iterative design, prototyping, embedded electronic devices, .NET Gadgeteer.

ACM Classification Keywords
H.5.2. Information interfaces and presentation (e.g., HCI).

General Terms
Design, Reliability, Experimentation, Human Factors.

INTRODUCTION
Research in domains such as ubiquitous computing, human-computer interaction, mobile computing and tangibles frequently involves the design, construction and evaluation of new forms of electronic device. A growing number of tools for prototyping such functional systems exist, incorporating a range of novel and powerful schemes for accelerating development and deployment. However, to date there has been little discussion of how to craft the form-factor of a prototype in a robust and high-fidelity way in parallel with the development of its function.

In this paper we start with a brief review of previous work which has addressed the issue of prototyping functional systems. We then present a series of example prototypes which have been constructed using the same underlying technology platform but which leverage a range of different physical prototyping techniques. We have divided these physical prototyping styles into eight broad categories and in each case we give an overview of the salient aspects of the approach along with any practical insights we have found to be particularly valuable. We end with a brief subjective analysis of the pros and cons of each category which we hope will inform others who are faced with a choice between them.

RELATED WORK
There are a number of established platforms for prototyping new electronic devices and a great deal of related research, see [13]. We summarize some of the relevant work here.

One of the most widely adopted prototyping platforms is Arduino [1], a processor board with a range of stackable shields (http://shieldlist.org/). Other stackable prototyping systems include PC-104 (http://pc104.org/), a variety of wireless sensing and processing systems e.g. [2, 10] and the BeagleBone (http://beagleboard.org/bone). Despite all these options, flexibility of construction is inherently limited with stackable systems. Although input and output elements like buttons, LEDs & motors may be connected on flying leads, tools to support this aspect of design are not common.

However, there is a great deal of work which does consider the form factor of new types of device. Variants of Arduino like the Seeeduino Film and Lilypad support compact, flexible and wearable form factors. Systems like d.tools [5], the Calder toolkit [8] and the commercially-available Phidgets system [4] have physical flexibility as a central tenet. Nonetheless, these tools do not typically allow the construction of standalone prototype devices. Peripherals which form the interactive elements of a prototype must be tethered to a standalone computer and as such they are not suitable for prototyping embedded electronic devices.

The final system we describe here is Microsoft .NET Gadgeteer [13]. This was designed from the outset to enable standalone functional devices to be constructed quickly and easily whilst simultaneously supporting flexibility in shape and appearance. Prototypes are constructed from modules connected to a central mainboard using 10-way miniature ribbon cables, typically 5-50cm long. This supports quick iteration during design, since modules may be quickly added and removed. Although modules vary in size they follow design guidelines including the size and position of mounting holes. There is flexibility in terms of relative position and orientation of each module and freedom in

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prototyping styles as well as form-factor. Gadgeteer is therefore a natural choice for comparing different techniques and forms the basis for the examples presented here.

PHYSICAL PROTOTYPING STYLES

1. Improvised physical development

One common approach to prototyping is to concentrate on functionality first, with minimal consideration of form factor. Figure 1 shows a prototype digital camera wired together using Gadgeteer, and illustrates what happens when it's picked up! If successful, a prototype like this inevitably needs to be tested further, given to other people, or evaluated in the field; even if the form-factor is not critical in itself, the prototype has to work reliably beyond the first few hours or days on the desk where it was created.

While it is possible to use improvised techniques such as taping modules to a sheet of cardboard or plastic to achieve physical robustness, a compelling yet fast alternative is the use of perforated sheets of material, described below.

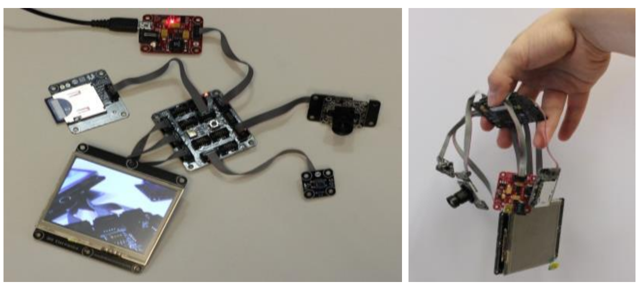

Figure 1. Functional prototype of a digital camera.

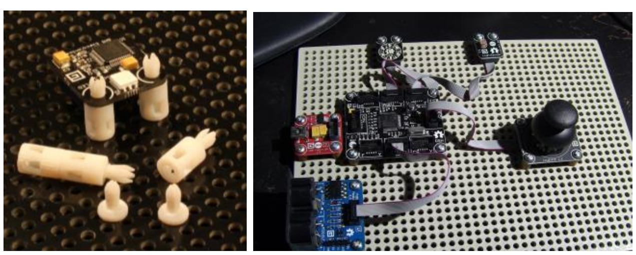

Figure 2. Perforated sheets can be used to secure electronic parts such as Gadgeteer. Left: Standard FR4 PCB sheet used with 3D printed end-stackable push-fit stand-offs. Right: A similar approach using off-the-shelf injection-molded plates and pop-rivets from Tamiya.

2. Adding robustness with perforated sheets and/or extruded aluminum frames

In most cases, the circuit boards which make up a prototype incorporate mounting holes. For example, the Gadgeteer specification requires modules to have corner mounting holes arranged on a fixed spacing, making it easy to mount them to a sheet of perforated material. We have used standard FR4 PCB fibreglass and also a system from the hobbyist model supplier Tamiya (http://tamiya.com), see Figure 2. Both of these use 3.2mm diameter holes on a 5mm pitch which is compatible with Gadgeteer and may be used in conjunction with off-the-shelf M3 stand-offs, 3D printed push-fit pillars and Tamiya push-fit pop rivets. We find this 2D 'pegboard' style of construction more visually appealing and much more robust than any of the ad-hoc techniques we have used. It's also quick and easy.

Alternatively, it's possible to use lengths of extruded 'T' slot aluminum such as Microrax (http://microrax.com) or Makerbeam (http://makerbeam.eu) to create a rigid framework for securing circuit boards using M3 machine screws.

3. Naïve control over form-factor

2D perforated boards limit the achievable form factor quite considerably. An alternative is to tape, glue or otherwise attach the various modules to whatever materials come to hand to form a 3-dimensional prototype. This is by far the most immediate form of physical prototyping and is a great approach when time is limited, e.g. during a 1-day workshop like the TEI Studio [12] and at after-school clubs for 14-15 year olds (see Figure 3). We have also seen 2D perforated sheets stacked both vertically and orthogonally to secure sets of components in particular configurations. Tamiya's right-angle mounting brackets are ideal for this.

Figure 3. Prototype devices produced during a school pilot use a wide variety of materials to produce the required form-factors. These include (from left-to-right) printed cardboard, vacuum-formed plastic, expanded polystyrene, cardboard/plastic, and felt-over-cardboard.

4. 3D 'Construction kit' prototypes

We have also experimented with the creation of 3D structures for prototype devices using off-the-shelf children's construction systems such as Lego, MegaBloks and K'nex. To incorporate functional electronic elements such as Gadgeteer modules, we have encased them in mating plastic enclosures. An example is shown in Figure 4.

5. More flexibility with papercraft-style construction

We have also developed a technique for basic control over the shape of a prototype using stiff cardboard to mount the components. Initially we used interlocking cardboard panels to which Gadgeteer components were mounted using screws and stand-off pillars, see Figure 5. More recently we have developed a papercraft-style construction approach which involves both cutting and scoring cardboard pieces in a laser cutter. The resulting designs are even simpler to construct, requiring only folding and slotting together. Through experimentation we have found it possible to mount components directly onto fold-out pillars which are oriented at 90° to each other (to reduce subsequent movement of the component). A cardboard camera built like this with Gadgeteer is presented in Figure 6.

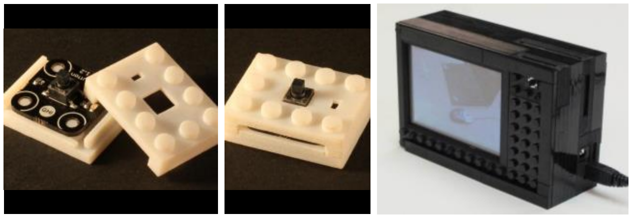

Figure 4. Enclosing a Gadgeteer module in a 'wrapper' makes it compatible with off-the-shelf construction systems. It is then possible to build prototypes such as this digital camera (shown at right) relatively quickly.

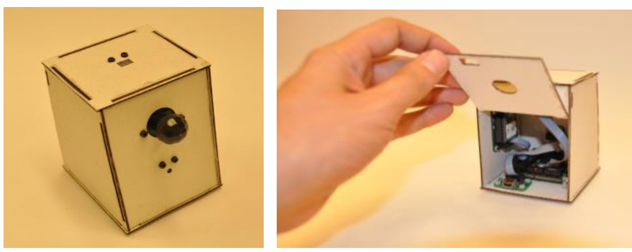

Figure 5. Cardboard is used to prototype a new type of passive infra-red sensing device [11]. Nylon screws hold the Gadgeteer components in place (at right).

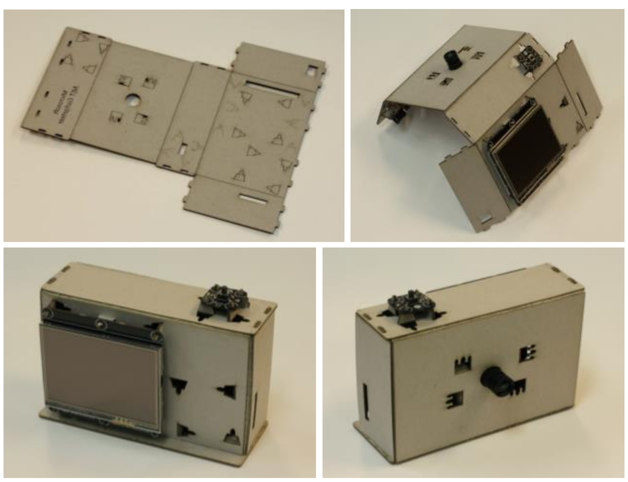

Figure 6. A cardboard digital camera case. Modules are mounted directly onto fold-out pillars and the unit fastens together in a 'tongue-and-groove' style; the display and pushbutton are external and everything else is internal.

6. Laser-cut frames and enclosures

It is possible to laser-cut an enclosure from a more robust material than cardboard, e.g. acrylic or plywood. In addition to basic flat-sided shapes, techniques such as kerf forming can be used to create simple curved surfaces. Having detailed CAD models of the relevant components is extremely valuable – by loading them into a single CAD assembly (e.g. in SolidWorks) it is possible to use features such as the edges of connectors, displays, buttons and mounting holes as references and thereby ensure perfect registration with the laser-cut pieces. In the case of Gadgeteer, detailed CAD models of all mainboards and modules are available online, see Figure 7 for some examples. Example devices are shown in Figure 8.

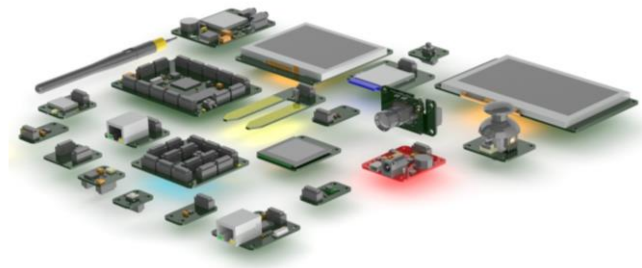

Figure 7. CAD models of components such as Gadgeteer modules facilitate the creation of custom enclosures.

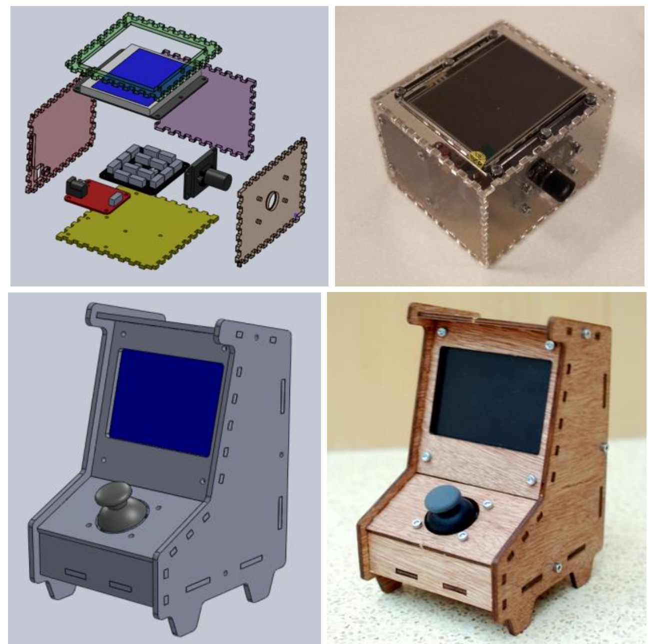

Figure 8. Bespoke enclosures created from laser-cut acrylic and plywood plates. 'Box Brownie' camera (top), mini arcade game (bottom). 3D models of the Gadgeteer modules are used (left) to ensure perfect fit (right).

7. Ultimate flexibility: 3D-printed enclosures

Another useful tool for creating prototype electronic devices with custom-built enclosures is a 3D printer. In our research we regularly use a Stratasys Dimension FDM printer. As with laser-cut enclosures, we leverage 3D CAD models to ensure perfect alignment of features such as mounting points and apertures. Mounting bushes may be incorporated in the 3D design, but because the FDM material is relatively soft we typically fit threaded brass inserts such as those from Tappex (http://tappex.co.uk) to increase the strength of the module mounting points. We have found that if the plastic bush is sized appropriately it is possible to fit the inserts quickly and securely by gently heating and pushing them with a soldering iron. An example 3D printed case is shown in Figure 10; the reader is referred elsewhere for other examples [3, 6, 7].

Figure 9. Retro-fitting an existing product is a great way to build a robust prototype with a very specific form factor. Here we show a Roberts radio which has been 'gutted' and retro-fitted with Gadgeteer modules.

8. Retrofitting an existing device

On many occasions we have found it valuable to 'retro-fit' an existing consumer device with prototype hardware and hence new functionality. As long as care is taken and suitably robust construction techniques and materials are used, this can be a great way to produce a robust prototype with a professional appearance relatively cheaply and quickly. In some cases it is possible to use rapid manufacturing tools such as a laser cutter and/or 3D printer to subtly modify and extend the enclosure of the original product. Figure 9 shows a transistor radio which was retro-fitted with Gadgeteer components to enable it to play digital sound recordings rather than live radio [9].

DISCUSSION AND CONCLUSION

In this paper we have presented eight different approaches to the physical construction of prototype electronic devices, and illustrated their use with examples built using Gadgeteer. Table 1 presents a subjective assessment of these categories in terms of six characteristics which we feel are important when considering which approach to use. Many compromises are readily apparent from the table. These approaches do not operate in isolation; it is possible to combine elements across them and to move between them when iterating a given design. For example Figure 10 shows a transition from cardboard to 3D-printed enclosures during the PreHeat project [11].

The prototyping techniques presented here are not exhaustive, nor are they sufficient for all types of device. For example we haven't considered clay modeling, casting and forming, or the use of textiles. Instead we have naturally focused on approaches which work well with Gadgeteer, our chosen hardware platform. In future we would like to extend this work to include other techniques and platforms. Nonetheless we hope that the approaches and observations reported here will help other practitioners building future prototypes using a variety of different tools and components. Moreover, this work may also be useful in informing the design of future prototyping platforms.

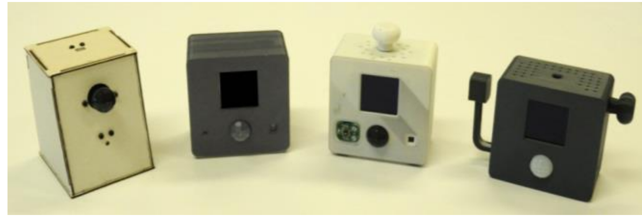

Figure 10. Iteration from cardboard to 3D printer.

1: worst … 5: best	Improvise	Peg-board	Naïve f-f	Const^n kit	Cardboard	Laser-cut	3D printed	Retro-fit
Speed to proto	5	5	4	4	3	2	2	1
Robustness	2	4	2	3	3	5	5	5
Form factor	2	1	2	2	3	4	5	5
Cost	1	3	1	4	2	4	5	4
Visual appeal	1	2	2	3	3	4	5	5
Reproducibility	2	5	2	3	4	5	5	1

Table 1. Comparison of prototyping approaches.

REFERENCES

1. M. Banzi, "Getting Started with Arduino" O'Reilly 2008.
2. A.Y. Benbasat et al: A Compact Modular Wireless Sensor Platform. In Proceedings of IPSN 2005.
3. B. Gaver and J. Bowers. 2012. Annotated portfolios. ACM Interactions 19, 4 (July 2012), 40-49.
4. S. Greenberg and C. Fitchett. Phidgets: easy development of physical interfaces through physical widgets. In proceedings of UIST '01 pp. 209-218.
5. B. Hartmann et al.: d.tools: Visually Prototyping Physical UIs through Statecharts. In Proc. UIST '05.
6. S. Hodges et al.: A New Era for Ubicomp Development. IEEE Pervasive Computing 11(1): 5-9 (2012).
7. V. Kalnikaitė et al.: How to Nudge In Situ: Designing Lambent Devices to Deliver Salience Information in Supermarkets. In Proceedings of UbiComp 2011.
8. J. C. Lee et al.: The Calder toolkit: wired and wireless components for rapidly prototyping interactive devices. In Proceedings of DIS '04. pp. 167-175.
9. D. Petrelli et al: FM radio: family interplay with sonic mementos. In Proceedings of CHI '10.
10. R. Sankaran et al.: Decoupling Interaction Hardware Design Using Reusable Electronics. In Proc TEI '09.
11. J. Scott et al.: PreHeat: Controlling Home Heating Using Occupancy Prediction. In Proc UbiComp 2011.
12. N. Villar et al.: .NET Gadgeteer TEI Studio 2011.
13. N. Villar et al.: .NET Gadgeteer: A Platform for Custom Devices. In Proceedings of Pervasive 2012.