

A Modular Architecture for Control and Communication Assistive Technology Devices

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### **Introduction**

The purpose of this paper is to propose a modular architecture for control and communications assistive technology (AT) devices that, if implemented, will provide individuals with disabilities solutions that have greater utility, lower cost, higher reliability, and greater personalization. Related benefits extend to providers of assistive technology – in particular schools, lending libraries, and disability specialists. The process of modularization through functional decomposition applied in this case has been practiced for over two decades (Baldwin & Clark, 2000; Sanchez & Mahoney, 1996; Ulrich & Tung, 1991), but there is little evidence that it has been applied to assistive technology.

I first became aware of this opportunity when performing a review of the assistive technology device landscape for an early course in my Master of Special Education studies. I browsed the listing of switches at the EnableMart and AbleNet websites, believing that switches must represent the simplest of all the assistive technologies. I was overwhelmed by the number and variety of options. I was also surprised by the apparent similarity between products by different manufacturers and even among products sold by the same manufacturer. Figure 1 presents a collage of red, mechanical, button switches available for purchase. A similar number of yellow, mechanical, button switches are also available. A closer look at the specifications and features of these switches reveals several independent attributes that affect the degree to which each would meet the needs and desires of a particular individual with a disability.

		
iSwitch (\$182)	Wireless Gumball Switch (\$115)	Big Buddy Switch (\$65)
		
Switch Click USB (\$140)	Moon Switch (\$40)	Bright Red Switch (\$166)
		
Orby Switch (\$42)	Gumball Switch (\$54)	Smoothie Switch (\$52)
		
Big Red Switch (\$65)	Jelly Bean Twist (\$65)	Big Beamer (\$190)

Figure 1. Red, Button-style Pressure Switches  
(images and pricing courtesy of the AbleNet and EnableMart websites)

Each mechanical button switch product available at the EnableMart and AbleNet websites represents, at first glance, a particular, fixed combination of about ten properties. An example of a property is the color of the switch button. One value for the button color property is “red”; another is “yellow”. If just three values of each property were possible, this space would include  $3^{10}$  or approximately 60,000 unique switch designs. In fact, a closer examination

reveals that there are over 20 properties (see Table A1). Several of the properties, like button size, can have many more than 3 values, while some properties, like presentation angle or activation force, should be completely flexible and under the control of the individual rather than a direct consequence of the switch housing design and mechanical switch choice. Each time a manufacturer chooses a value of a property to incorporate into the design of their switch, they limit the usefulness of that switch for individuals who would have been best served by a different value of that property.

Simple speech generating devices (SGDs) carry switch technology even further by adding voice recording and playback capabilities. All of the property options possible in the simple switch domain are applicable to SGDs, along with property options specific to voice recording, storage, and playback. Product designers, intending to gather these options into a neat package must, by definition, narrow their target market each time they choose one and only one property value for their product. If a product design does not fit the needs of a consumer, the consumer must find a way to accommodate the design of the product or reject it.



Figure 2. The iTalk2 with Levels by AbleNet  
(images courtesy of the AbleNet website)

For example, the iTalk 2 with Levels by AbleNet (Figure 2) includes the following fixed property values:

- switch count: 2;
- switch type: mechanical;
- activation surface type and colors = smooth plastic, red and yellow;
- activation surface shape and size = round, 2.5 inches;
- activation force and distance: unspecified (but fixed);
- inter-switch distance and ridge = 3.5 inches, yes (1/2 inch above activation surfaces);
- support for a 2 dimensional object reference;
- activation surface presentation at a 45-degree angle;
- base color: black;

- mounting system: rubberized feet, must sit on a sufficiently frictional, horizontal surface;
- significant manual dexterity required for level selection, recording initiation, and on/off/volume control; (controls are visible in Figure 2, images C and D)
- max volume: unspecified (but fixed);
- three message levels and two messages at each level for a total of 6 messages;
- live-message recording (normally voiced by a family member or caregiver).

The above list represents just a few of the specific feature implementation decisions made by this and other manufacturers. Each device is attempting to address a general set of user needs. Unfortunately, this thinking is directly opposed to what we know about individuals with disabilities. “An individual with a disability has unique personal characteristics, unique environments, and specific activities to which they apply technology devices and require AT services” (Clayback, Hostak, Leahy, Minkel, Piper and Smith, 2015, p. 41). It is possible, but unlikely, that these fixed property values match exactly the needs and desires of the user for whom the iTalk2 has been selected. It is more likely that the user will have to make compromises and have to expend additional effort to utilize the device with a concomitant loss of performance or usage. In addition, there might be features built into the product (e.g., the external switch inputs visible in Figure 2 image D) that add to the cost and reduce the reliability of the device but have no value for the user.

Integral or monolithic packages, like the iTalk 2 with Levels, can be beneficial in that they can claim “No Assembly Required.” Management of and documentation for components are simplified. That work has already been done by the manufacturer. The manufacturer will often protect their assembly behind a housing. The housing can protect delicate parts from

inadvertent actions of the user and can protect the user from potentially dangerous mechanical and electrical parts. Most of all, it ensures that the product's components have a predictable operating environment, accessible only by the manufacturer. That predictable and protected environment normally means that the manufacturer can manage cost by reducing or eliminating redundant and resilient components. Failure of a component can, and often does, result in failure of the entire product. When an AT device has become integral to and an extension of the individual with a disability, this failure can have a significant impact on their independence and integration into the community.

The more functionality that manufacturers build into their devices, the more the devices cost to obtain. Individuals and institutions often cannot afford to keep one or more backup copies of a device on hand in the event of failure of a primary device. When an AT device must be returned to the manufacturer for diagnosis and repair, it could be days or a few weeks and at a cost approaching seventy-five percent of the price of the original product (personal communication with AbleNet Customer Service) before the individual with a disability can be returned to normal functioning.

In this paper, I will make the case that by carefully decomposing these product designs into a collection of smaller, interchangeable modules, one can quickly assemble systems with the same capabilities at lower cost, with higher availability, better fit and utility, and greater opportunity for personalization. I am not proposing to re-architect this domain from scratch. Decades of design, testing, and usage have gone into these products. Maier and Rechtin (2002) recommend that, during the architecture process, "extensive reuse of existing modules should be expected because design assumptions, system functions, and interfaces are largely unchanged" (p. 39). At the same time, they say, "Don't assume that the original statement of the problem is

necessarily the best, or even the right one” (p. 28). I will demonstrate how a thoughtful modularization can drive down cost by reducing complexity and leveraging standards and technology available to the general public. I will show that modularization makes it possible for manufacturers to provide the custom solutions demanded by modern customers and, at the same time, frees designers to innovate and incorporate new technologies and processes into their products. Finally, I will demonstrate that anyone can become a “manufacturer” through the use of 3D printing and crowd-sourced design. All of this will create a world of AT in which devices fit users rather than users accommodating devices, and one where individuals with disabilities can readily connect to and leverage the standard technologies available to the general public, now and in the future.

## **Review of the Literature**

### **Architecture and Design**

Ulrich (1995) defines an architecture as an arrangement of functional elements mapped to physical components with a specification of the interfaces between interacting functional and physical components. Architecting is the process by which architectures are created. Unlike engineering, architecting is focused more on the use of heuristics and closeness to the client and less on analytics ( Dahmus, Gonzalez-Zugasti & Otto, 2001; Maier & Rechtin, 2002). Heuristics are “abstractions of experience, trusted, nonanalytic guidelines for treating complex, inherently unbounded, ill-structured problems” (Maier & Rechtin, 2002, p. 34).

The primary heuristics used in this proposal (Maier & Rechtin, 2002) are:

- The eye is a fine architect. Believe it. A good solution, somehow, looks nice.
- The architecture of a support element must fit that of the system which it supports. It is easier to match a support system to the human it supports than the reverse.



- Choose the elements so that they are as independent as possible; that is, elements with low external complexity (low coupling) and high internal complexity (high cohesion).
- Except for good and sufficient reasons, functional and physical structuring should match.

A system is a collection of parts or components that can produce results that would be unachievable by those same components in isolation. The collection of components and their interrelationships define the system. These interrelationships between components are more specifically referred to as component interfaces. An interface may be anything from the mechanical mating of parts to a complex sharing of data and decision making. A system with well-defined component interfaces allows for those components to be shared easily across products and product lines (Marion, Meyer & Barczak, 2015). A flexible architecture is composed of basic, flexible, and individualized components (Li, Cheng, Feng & Yang, 2013). Basic modules are those that provide standardized, universal, and fundamental functions that can be applied across a series of products. Flexible components are those that are parameterized and can be modified to serve unique needs but retain their basic form. Individualized components are developed to perform a specific function and serve to differentiate among products in a portfolio. “Taking a systems approach [to architecture] means paying close attention to results or the reasons we build a system. Architecture must be grounded in the client's/ user's/ customer's purpose. Architecture is not just about the structure of components” (Maier & Rechtin, 2002, p. 8). This paper attempts to specify an architecture for components in the domain of control and communications AT that supports products which can more closely achieve the goals of individuals with disabilities.

**Universal design and user-centered design.** There has always been a tension between design for all and design for the individual (Lewis, Langdon & Clarkson, 2006; Reed & Monk, 2006). To be successful, manufacturers must design for the largest market of customers possible but, in general, each customer wants the best solution for themselves and could care less about the market as a whole. Universal Design (UD) is an attempt to build certain principles into the design process and thereby produce a result that will have a high probability of meeting a wide variety of needs and expectations. In 1997, the Center for Universal Design at North Carolina State University established seven principles of UD to guide the design process or be used to evaluate existing and proposed designs (Cook & Polgar, 2002; Flagg, Lockett & Lane, 2015). User-Centered Design, instead, focuses on a targeted set of users and understanding their specific needs and limitations. Representatives of the target population are then directly consulted and included in each iteration of the design process (Ladner, 2010; Polgar, 2010; Reed & Monk, 2006). Choi (2010) found that user involvement in the design process is the largest factor in predicting user satisfaction and effective use of the final product. User-Centered Design is sometimes referred to by the more generic term Inclusive Design.

Inclusively designed products tackle the disparity that has arisen from a design culture dominated by young, non-disabled, males. Most products fit the stereotype of their designers, ignoring an increasing number of users who vary from mild to severe impairment and corresponding disability in society. (Lewis et. al., 2006, p. 189)

Given the challenges faced by individuals with disabilities, it is no surprise that most designers of AT choose User-Centered Design as their development process (Choi, 2010).

The individuals at CanAssist, a program associated with the University of Victoria in British Columbia, Canada takes the process a step further.

All projects undertaken by CanAssist are in direct response to requests – either directly from the individual with special needs or from a family member, caregiver, or health care-professional acting on their behalf. Before a project proceeds, the client coordinator talks with or preferably meets with the prospective user (and/or representative) to clearly understand the user’s needs and the context of the request. (Cook, Polgar & Livingston, 2010, p. 9)

Any technology that comes out of the process is then evaluated for its general application within the disabled community, and, if it is found to have greater applicability, then it may be offered for sale by the program. However, development and profitable sales of AT products is not the focus of the program – a strategy that can only be adopted by publicly funded entities like universities.

**Existing architectures/infrastructures/frameworks for AT.** A SUMMON search through the BGSU Library system for scholarly texts on the topics of “assistive technology” and “architecture” within the last five years returned thousands of results. The 100 most relevant results were articles that:

- were computer or software architectures
- used the word architecture in its “home design and layout” sense
- were authored by individuals in colleges of architecture
- strangely, did not actually use the word architecture anywhere in the article
- were about the design and evaluation of a prototype device to meet a specific need
- used the word architecture simply as an organized set of elements

Typically, the articles did not include the word architecture in the title, abstract, or list of keywords.

In all, only four articles or books purporting to describe an architecture or framework associated with AT were found. Mulfari, Celesti, and Villari (2015) describe a cloud-based architecture for compiling and distributing configuration settings established by users of AT software to facilitate creating environments on new virtual machines. Moody (2015) proposes a set of procedures for developing assistive technology demonstration and lending sites based on her own experience and information gathered from the CAST ([www.cast.org](http://www.cast.org)) and Wisconsin Assistive Technology Initiative (WATI) organizations ([www.wati.org](http://www.wati.org)). Danail-Saad, Kuflik, Weiss and Schreuer (2013) describe an ontology – a classification of definitions and concepts – specific to AT pointing devices in an attempt to identify the most significant features of pointing devices (e.g., size, ease of mounting, portability) and how they relate to physical features of the users based on input from AT experts. In a personal communication with Glenn Hedmann, current chairman of the Rehabilitation Engineering and Assistive Technology Society of North America (RESNA), Assistive Technology Standards Board (ATSB), regarding whether there existed any architectures for assistive technology, his response was to look to the product categorization at the AbleData website ([www.abledata.com](http://www.abledata.com)) or look to the Cook and Polgar text (2002) to see how they categorized AT.

Hedmann's response reflects the common confusion between the concepts of "categorization" and "architecture." A categorization is simply an attempt to place items into classes or groups based on some rationale. The rationale can be completely arbitrary but is normally intended to make it easier to search for items of interest and to discover items of similar design and content. Architecture is more concerned about the interrelationships between entities with respect to the behavior and goals of a larger system. An examination of the AbleData website confirms its emphasis on categorization. "The ABLEDATA database classifies each

assistive technology product by its intended function or any special features it possesses” (Cook & Polgar, 2002, p. 24). Ironically, Clayback et. al., (2015) are critical of websites like AbleData as a source of information about AT devices:

While numerous websites and apps have recently emerged, including federally supported programs such as AbleData that solicit consumer feedback on ATDs, these systems have only been used minimally. (AbleData notes are available on less than half of 1% of products with usually only one entry.) And these systems provide minimal data regarding user context or elicitation of common coding variables for comparison. The environment is ready for a more accessible and complete approach toward data collection. (p. 48)

Cook and Polgar (2002) do provide some useful terminology when thinking about the architecture of control AT devices. They describe three elements that comprise the control domain for AT:

- Control Site: a part of the human body that can be used to control a device
- Control Interface: the hardware by which a human can control his or her environment (sometimes called an input device)
- Processor: the component in an assistive technology system that relates and translates information from the control interface into an action on the user’s environment

Cook and Polgar provide additional detail and terminology in each of these areas that will be used later in this document to describe AT control systems and their properties – in particular the concept of an activation surface and its properties.

**Successful design.** Before leaving the topic of architecture and design, it is important to describe what constitutes the successful development of an architecture or product design.

Dahmus et. al. (2001) characterize an ideal architecture as:

One that partitions the product into practical and useful modules. Some successfully designed modules can be easily updated on regular time cycles, some can be made in multiple levels to offer wide market variety, some can be easily removed as they wear, and some can be easily swapped to gain added functionality. (p. 410)

Stapleberg (2009) admonishes the architect or engineer to ensure that reliability, availability, and maintainability have been accounted for in the design.

Life cycle, reliability, availability, and maintainability are design concepts that fall under the rubric of Design for X which heavily influenced the proposed architecture in this document. At the same time, Design for X is heavily dependent on modular architectures to achieve its varied goals. Finally, Maier and Rechtin (2002) recognize that successful architectures are “open” – meaning that they make expansion and extension easy for third parties. Third parties often play a critical role in feeding the market need for constant improvement and innovation in the life of a product. Design for Openness is not a traditional element of the Design for X philosophy – but it easily could be.

### **Assistive Technology and Individuals with Disabilities**

The term “assistive technology” refers broadly to a range of devices and services that are provided to individuals with the intention of alleviating or mitigating the difficulties they face as a result of a disability. Assistive technology can take two forms – a device or a service. AT devices and services have largely been defined by United States Code (U.S.C.) associated with the Individuals with Disabilities Education Act.

*An assistive technology device* refers to “any item, piece of equipment or product system, whether acquired commercially off the shelf, modified, or customized, that is used to increase, maintain, or improve the functional capabilities of a child with a disability” (20 U.S.C. § 1402(1)(A)).

*An assistive technology service* is one that:

directly assists a child with a disability in the selection, acquisition, or use of an AT device. These services include: (1) an evaluation of the AT needs of an individual with a disability; (2) purchasing, leasing, selecting, designing, fitting, customizing, adapting, applying, maintaining, repairing, or replacing of AT devices; (3) coordinating and using necessary therapies, interventions, or services with AT devices; (4) training or technical assistance for an individual with disabilities, or, where appropriate, the family members, guardians, advocates, or authorized representatives of such an individual; and (5) training or technical assistance for professionals (including individuals providing education and rehabilitation services), employers, or other individuals who provide services to, employ, or are otherwise substantially involved in the major life functions of individuals with disabilities.” (20 U.S.C. § 1402(2))

Because these laws speak of AT in terms of its role in education, they are specifically associated with “a child” with a disability. However, assistive technology devices and services can be useful in helping individuals of all ages function more effectively at home, in school, in the workplace, and in the greater community. In the case of a child with a disability, additional regulations require that schools develop Individualized Education Programs (IEPs) for each child with a disability and that as part of developing the IEP schools must “consider a student’s need

for AT devices and services” (20 U.S.C. § 1414(d)(3)(B)(v)). If it is determined that a child needs AT devices or services to meet their educational needs then:

Each public agency shall ensure that assistive technology devices or assistive technology services, or both, are made available to a child with a disability if required as a part of the child’s special education under, related services or supplementary aids and services. (34 C.F.R. § 300.308)

Whether we are talking about children or adults, AT in general and AT devices in particular address a broad spectrum of needs – from seating, positioning and mobility to blind and low vision to reading and writing. This document will focus on AT for control and communication, but the process of functional decomposition and modular architecture can apply across the AT spectrum.

**The role of assistive technology in the life of a user.** Ladner (2010) prefers the term “accessible technology” over “assistive technology” because the latter carries a “paternalistic notion of needing assistance” (p. 8), while the former is a better fit to the social model of disability and emphasizes the role of AT in making human activities more accessible to all individuals. The social model of disability recognizes that disability is just a natural part of the diversity of life (Borisoff, 2010; Macdonald, 2006). It is natural, as part of the aging process, that individuals lose motor and sensory capabilities and can benefit from the AT originally developed for much younger individuals with disabilities. As a result, AT is simply part of that diversity of human experiences and, as time goes on, the original motivation for the development of AT (as an aid to children and young adults or as an aid to seniors) will blur and become irrelevant.



At the same time, everyone is to one degree or another defined by their possessions. You are the car you drive, the clothes you wear, and the home in which you live. This is particularly true of assistive technology and the individuals who use it (Csikszentmihalyi & Halton, 1981). Because AT connects individuals with disabilities to the world around them it becomes an extension of the individual's motor and sensory self (Allen, 2005). However, "in many cases, the very devices intended to assist people with disabilities in fact do damage: they compound people's disabilities by drawing attention to impairments" (p. 139). This creates an odd tension for the user. The AT is a part of themselves that they value highly and yet it is the very thing that can lead to their stigmatization. Alternatively, highly visible AT (i.e., an SGD as opposed to a hearing aid) can become a point of fascination for others and draw attention away from the user as if the AT were another entity in itself (Polgar, 2010). In response to the challenges of selecting and adopting AT for students, Bouck, Shurr, Tom, Jasper, Bassette, Miller & Flanagan (2012) emphasize that AT devices must be transportable, available, practical, and engaging.

One must take this knowledge into account in the design of an AT device – that it will become part of the self-identity of its user and so should reflect the user's personality, that it should be invisible if possible (or at least camouflaged) or, if it must be visible, that it should be inviting and engaging but not detract from the user. Given the "unique personal characteristics, unique environments, and specific activities to which they apply technology devices and require AT services" (Clayback, et al., p. 41) this can be an extremely challenging assignment.

**The market for AT and its implications.** For the most part the market for AT devices is an unattractive one from an economic standpoint. The number of consumers is small, their needs are too varied, and the funding/payment process is complex and often insufficient (Lewis & Matsuoka, 2010). There is no obvious "sweet spot" to build large scale manufacturing around.

“The number of people who have exactly the same need, and for whom the same device will meet the need, is small” (Cook & Polgar, 2002, p. 23). In addition the supply chain is long and involved with multiple stakeholders, the devices often require education and training for each stakeholder, regulatory requirements abound, and maintenance requirements can be complex.

A start-up company will find it difficult to raise money for its ideas that address a small market. A rule of thumb for pursuing venture capital is whether it is possible in the short-term (e.g., less than 5 years) to attain \$100 million in annual revenue. Many successful AT companies that have been operating for decades have sales only in the low tens of millions of dollars. It is not uncommon for AT companies to have sales that are even smaller. (Borisoff, 2010, p. 106)

Most AT companies are small and address niche markets (Borisoff, 2010; Choi, 2010). Small markets mean small production runs with little opportunity for economies of scale, therefore, the cost of production per unit is relatively high in comparison to mass production. That leaves little room for profit and the costs described above of meeting regulatory requirements, complex sales channels, and significant maintenance challenges eat further into profits. As a result, small AT companies tend to stay small. A small staff that is largely devoted to sales and maintenance leaves little room for improved design and innovation, as well as a generally conservative managerial mindset that is reluctant to change their product or only offers small improvements in the device over time. The result can be a product with hosts of minor features that no one uses. They can distract and confuse users who are trying to use the simple features for which the product was initially developed (Lewis et. al., 2006). The solution to this problem normally involves a re-architecture effort that will partition the features into different

areas of the user interface or into different products. Small companies with conservative mindsets and limited budgets have little interest in performing a re-architecture.

Larger manufacturers see little economic incentive to enter the business of AT. In addition, they see little incentive to make the products that they produce accessible to individuals with disabilities either directly or through integration with an AT device (Livingston, 2010). The domain of electronic consumer products is one of the fastest growing sectors of the American economy, but there is little opportunity for the disabled community to benefit from this advancement. At the same time, the number of companies developing technology for individuals with disabilities remains small, therefore, the number of technologies available remains scarce and stagnant (Lewis & Matsuoka, 2010). The end result is that many individuals with disabilities are unable to obtain the personalized technology that would address the physical and cognitive challenges they face in the workplace and the greater community (Livingston, 2010).

### **Modularization**

Mikkola (2000) defines modularization as the development of a product architecture that provides opportunities for arranging and substituting components in order to support a wide range of variation in product behavior. Modularization requires that the functionality of each component and the interfaces provided by each component be well understood and well defined. A modular architecture allows customers to determine the look and behavior of a product rather than being forced to accept a package that has been predetermined by the manufacturer (Shamsuzzoha, 2011).

Modularization also provides benefits to the manufacturer in that a wide variety of products can be offered to customers simply by creating them at assembly-time (termed “configure-to-order”). There is less need to forecast sales of custom solutions because

manufacturers can respond to demand almost immediately. Similarly, there is less of a requirement for inventory management and less cost associated with that inventory since only the components have to be retained. This translates into economies of scale and economies of scope (Shamsuzzoha, 2011). Assistive Technology Professionals (ATPs) can also take advantage of modular product architectures by assembling AT devices that best fit the needs of a client while working with the client. ATPs can use the same approach to managing inventory and overall cost by retaining a mix of components that represent the typical desires and interests of his or her clients. Creating products at assembly-time is a type of “late-binding” or “just-in-time” manufacturing.

Modular architectures can be improved and upgraded easily by replacing components without impacting the functions of unrelated components. As a result the product can continue to remain viable and can continue to grow in the market (Marion et. al., 2015). Because modular components are designed to function independently of other modules they can also be improved upon in quality, functionality, and aesthetics in isolation of the other modules as long as documented interfaces are maintained (Shamsuzzoha & Helo, 2012). Even the U.S. Environmental Protection Agency has weighed in in the support of modular product architectures because they tend to produce less waste as products are upgraded. Only the upgraded component is disposed of (Agrawal, Atasu & Ülkü, 2016).

Modularity is not a panacea. There can be good reasons for creating monolithic and integral products. In particular, a modular system “may sacrifice a certain amount of performance optimization” (Shamsuzzoha, 2011, p. 26) but this is an architectural decision as all cost, functionality, and performance decisions are. The popularity of “configure-to-order”

product lines like computers, cars, cable television packages, and Chinese menus would attest that the benefits of modularity usually outweigh the costs.

Modularity supports creative design. In an exercise to develop a augmentative and alternative communication (AAC) system for the students at Portland College, an independent college for people with disabilities in Mansfield, Nottinghamshire, UK, Allen (2005) was able to design unique packaging for the components of the system. The user interface (computer screen and keyboard) was packaged as a leather-bound book. The computer processor and battery pack was sized to fit in a waist pack and the speaker was packaged to look like a mobile phone. The format of a leather-bound book provided an air of sophistication and intelligence to the user – providing “meaning through semantics and metaphor” (p. 142) – while the phone-like speaker allowed for private communication with a partner who simply appeared to be on a phone call. Finally, putting the heavier electronics in a standard waist pack distributed the weight of the system appropriately, protected the components from the weather, and gave the user the “fashion choice” of which pack to use. This sort of creative aesthetic design is limited or even impossible with monolithic systems.

**Methods of modularization.** Modularization is a process of aggregation and partitioning, composing and decomposing (Maier & Rechtin, 2002). According to Maier and Rechtin, “the most important aggregation and partitioning heuristics are to minimize external coupling and maximize internal cohesion” (p. 180). This fundamentally means to define components so that they are as independent as possible. Maximizing internal cohesion means that all functionality with the component should be closely related. If there is a high degree of cooperation and communication between elements of a system then they should, most likely, be located in the same module. If these elements then need to obtain or provide information to

some other element then the partitioning should be such that that communication is naturally minimal and infrequent in its nature. Certainly, elements of the system that have no direct communication with each other should be assigned to different modules.

More formal modularization methods exist for analysing the structure of system and are normally applied to complex systems where the manufacturer can incur significant costs over an extended timeframe. As a result, it is worth the manufacturer making a significant investment in the analysis. Such methods include Design Structure Matrix, which diagrams all system components according to the other components that they share interfaces with and looks for clustering (Steward, 1981). Stone, Wood and Crawford (1998) propose another method, referred to as the dominant flow heuristic, based on information flow through the system and prioritizing the flows.

There are alternatives to partitioning on the basis of connectivity and communication. These alternatives look at similarity among functions (Borjesson & Hölttä-Otto, 2014). These similarities can exist on any number of dimensions, strikingly like the X's in the Design for X lexicon. Some common bases for similarity might be:

- elements with similar failure rates
- elements with similar assembly characteristics
- elements already available in a pre-assembly
- elements likely to evolve/innovate at the same rate
- elements that are commonly requested in unison by customers
- elements that are core to or strategic for the product line versus those that are peripheral

Huynh and Cai (2007) implicitly draw a connection between modularity and Design for X when they state, “Modularity in design is immensely important for software systems, determining software quality in terms of evolveability, changeability, maintainability, etc.” (p. 1) – all of which are aspects of Design for X.

### **Design for X**

Sreekumar (2013) describes Design for X as a shorthand for “Design for Excellence.” That may be the case, but it has simply come to mean that architects and engineers have a well-worn collection of goals that their designs need to meet and a successful project will consider all of those goals. Each goal may not be optimized but each will be given sufficient thought to determine its relative contribution to the success or failure of the project and a design effort will be made to mitigate or minimize the impact of any goals that could not be directly addressed. The X in Design for X is intended, like a variable in algebra, to serve as a placeholder for the name of each design goal. The following discussion will expound upon the more well-known goals and suggest a few new ones specific to the domain of AT.

**DFV – Design for Variety.** The design goal of supporting and managing variety in a product is a relatively recent one. Tradition has it that Henry Ford once quipped in 1909 that a customer could “have any color as long as it's black” in reference to his Model T. Similar attributions have been made to AT&T regarding the phone they provided to the masses. Ford has had serious competitors for a long time and AT&T lost its monopoly on phones in 1986. The result has been a laser focus on the desires of the customer and not the preferences of the manufacturer. Customers have gotten used to the idea that any product they buy will come in multiple colors, sizes, feature sets, and model numbers. Manufacturers who do not provide this sort of variety suffer a loss of market share or are unable to enter the market at all.

It is now critical for manufacturers to plan for and manage variety in their product and service offerings. “Most products grow into a massive variety to mainly accommodate different customers’ needs. Variation exists regardless of the structural complexity of products, which might be as simple as a light bulb or as complex as an automobile” (AlGeddawy & ElMaraghy, 2012, p. 518). They accomplish this aim through a process called “Form Postponement” or “Delayed Product Differentiation (DPD)” meaning that final product configuration and assembly is delayed until a customer request for that specific configuration has been received. Anyone who has recently purchased a laptop computer from Dell will be familiar with the process by which one “assembles” their future computer via the Dell website, and Dell will keep them informed as their computer then proceeds through the assembly process. In order to make DPD possible, the manufacturer must be confident that each configuration of components will function as expected. That requires that each component has minimal dependencies on other components (i.e., components must be loosely coupled). Modular design and architecture assures that this characteristic of the system will be attained.

For individuals with disabilities, variety (read customizability) is critical. As previously stated, the needs and capabilities of these individuals are incredibly varied and their ability to simply accommodate a product which does not completely meet their needs may be non-existent. As a result, this paper proposes a modular architecture that emphasizes and facilitates variety and customization.

**DFA, DFDA – Design for Assembly/Disassembly.** If configuration and assembly of a product are to wait until just before delivery to a customer, the assembly process must be highly efficient. Design for Assembly and Disassembly looks at the product structure with an eye for how components will be brought together in the final product or disassembled for the purpose of



upgrade or troubleshooting and maintenance. A more sophisticated view of DFA/DFDA will ensure that certain components can be removed from an assembly and replaced without affecting the major functions of a live system (Sreekumar, 2013). An optimally designed product will allow customers themselves to perform the disassembly and reassembly associated with upgrade or maintenance.

Because Design for Variety/Customization is a driving force for the architecture proposed in this paper, Design for Assembly must also be a priority. In many cases this translates into simple plug and play components and in others into use of de facto standards for mounting interfaces. The expectation is that a proper modular architecture will put the configuration, assembly, upgrade and maintenance process into the hands of the ATP with no need to involve the device manufacturer except for the most rare and difficult issues.

**DFR – Design for Reliability.** Product reliability is formally defined as the probability that a product will perform its function under specified operating conditions for a specified length of time. In most cases the specified length of time is the expected product life. Because each function performed by a product can involve the successful operation of multiple components, the inherent reliability of each component contributes to the overall reliability of the product. The more important a particular function of the product, the higher the reliability of the components that support that function must be (Stapelberg, 2009).

The reliability of a system can be calculated based on the reliability of the components and their interrelationships. The reliability of two components connected in series (one after the other) is the product of their individual reliabilities. Because reliabilities are represented as values between zero and one, the reliability of components connected in series is always less than the reliability of the worst component in the chain. This is the basis for the adage that a

chain is only as strong as its weakest link. It is also the reason to be very aware of components, connected in series, that contain a low reliability element. These elements are often referred to as a “single point of failure” for the system if their failure will have a profound effect on the functionality of the system. Simple AT devices like switches and simple speech generating devices are rife with single points of failure. Something as simple as the failure of the rheostat-style volume control in an SGD will render the entire SGD non-functional. Highly reliable systems are often very expensive to design and build. That expense would necessarily be passed on to the consumer. In a market with all the burdens that already exist for AT companies, high product prices could be suicidal so it is not surprising that simple AT devices would be characterized as generally unreliable.

However, users do not directly experience the “reliability” of products and components. Instead they experience the “availability” of a product. A product that fails frequently but recovers almost immediately may not be perceived as having failed at all.

**DFAv – Design for Availability.** Availability takes into account two separate events—the failure of a critical component (one that causes the cessation of a desired function) and the point in time when the failed component has been repaired and the system is back at operational capacity (Stapelberg, 2009). The period of time when the desired function of a product is unavailable is referred to as the “downtime” of the product and the time necessary to affect a repair is referred to as the “time to repair.” The shorter the time to repair, the smaller the downtime and the larger the available time of the product.

For individuals who rely on their AT to be functioning properly in order to retain their independence and remain connected to their friends, family, and community, product availability is of paramount importance. Availability can be managed in a domain of inherently unreliable

products by minimizing the time to repair (or in its probabilistic sense, the “mean time to repair,” MTTR). MTTR is the primary focus of Design for Maintainability.

**DFM – Design for Maintainability.** Maintainability is the ease with which a system can be kept in a state of normal operation - in other words, its stated functionality, usability, reliability and quality (Sreekumar, 2013). Maintenance comes in two forms: preventive and corrective. Preventive maintenance is carried out to reduce the likelihood of a failure of a component or system while corrective maintenance is performed in the event of a component or system failure. Preventive maintenance is proactive while corrective maintenance is reactive. Design for Maintainability is focused on reducing downtime, which as we have seen above directly impacts product availability. “Designing for maintainability, as it is applied to an item of equipment, includes the aspects of visibility, accessibility, testability, repairability and interchangeability of an assembly’s inherent components” (Stapelberg, 2009, p. 20). The “interchangeability of an assembly’s inherent components” is a direct result of the low-coupling property of the components and is therefore dependent on the degree to which the product architecture is modular. Testability is also dependent upon the independence of components and direct result of modularity (Maier & Rechtin, 2002).

The proposed architecture in this paper will recommend that the process followed when testing and repairing an AT device, and thereby minimizing the repair time of the system, involves simply swapping out interchangeable, low-cost components. Given that most of these simple components are connected in serial fashion with little interdependence, and the likelihood of the simultaneous failure of two components is small, a failed part can be identified when its replacement works while the original did not. To facilitate the process of testing and repair, the

architecture must demonstrate a high degree of design for assembly/disassembly (which correlates to the concepts of visibility and accessibility listed above as key to maintainability).

The cost to find and fix an inadequate or failed part increases by an order of magnitude as it is successively incorporated into higher levels in the system. The least expensive and most effective place to find and fix a problem is at its source. (Maier & Rechtin, 2002, p. 276)

Bundling components into a sealed, monolithic package is the functional equivalent of incorporating the components into a higher level of the system. Making repairs to one of these monolithic systems requires returning the product to the manufacturer which is accompanied by significant repair costs and downtime (lost availability).

Supportability is sometimes used in place of the term “maintainability”. Tortorella (2015) makes several recommendations for product design that can enhance supportability. Among them are he calls for the use of “use standard fasteners and tools, wherever possible, and to use fastenerless assembly (such as snap fastening) where appropriate” (p. 382). The architecture described in this paper makes liberal use of hand-snapped, hand-screwed, and hand-plugged components. Though mentioned here as valuable to the maintenance process they are fundamentally driven by Design for Assembly/Disassembly.

**DFC – Design for Cost.** “Clearly, if a system is to succeed, it must satisfy a useful purpose at an affordable cost for an acceptable period of time” (Maier & Rechtin, 2002, p. 10). Rather than model design after the traditional methods of Design for Cost like performing cost modeling and prediction throughout the design process, the recommendations in this paper will directly address the low batch size nature of the AT market and leverage new technologies of Rapid Manufacturing/Prototyping to drastically drive down the costs associated with what would

otherwise be “one-off” products - products which incur significant setup costs and cannot benefit from small incremental production costs. This topic will be addressed directly in the section on the application of 3D printing to AT.

**DFI –Design for Innovation.** Innovation is not a traditional X in the lexicon of Design for X. Like Design for Variety it is a relatively recent phenomenon driven by the performance improvements in information technology. The realization that Moore’s Law has effectively characterized the performance of integrated circuits from 1965 until today, and the concomitant innovations in consumer electronics, has created an expectation on the part of customers that product upgrades and innovation are givens and any manufacturer who does not rapidly innovate and delight must be deficient (Krishnan & Ramachandran, 2011). Consider how, on the eve of a new iPhone release, the prominent topic of discussion is when the next iPhone will come out. Any delays lead Apple customers to question whether the management team at Apple has lost its edge.

A modular architecture is critical to product innovation. If components drag other components around like a ball and chain, designers are not free to experiment with and redesign such a component because of the potential negative effects on the related components. Just the opposite is true for a modular architecture where each component is free to change and innovate as long as the interfaces to related components remain stable (Wu, Matta & Lowe, 2009).

Borisoff (2010) singles out the inherently small AT market as having the potential for fostering technological innovation. Large markets, by their nature, have a large embedded base of products and customer which produces a natural inertia. Small markets can innovate and redefine themselves without obtaining the buy-in of a huge set of customers and sales channel partners. Unfortunately, while small markets have less inherent inertia, the manufacturers who

live and breathe there operate on such thin margins that they have developed an inertia of conservative thinking.

This paper makes the proposal that innovation in the AT domain can blossom if the costs of development and manufacturing are driven almost to zero through rapid manufacturing and crowd-sourced design. The architecture in this paper is intended to facilitate that change.

**DFLC – Design for Life Cycle.** Design for Life Cycle takes the architecture and design process beyond the day-to-day functioning and maintenance of the product and considers how early design and planning can plan for the entire life cycle of the product including disposability, recyclability, reusability and upgradability. Again, modular design is key to increased performance in each of these lifecycle stages (Umeda, Fukushima, Tonoike & Kondoh, 2008). When modularizing a product for life cycle, the designer groups elements that are similar with respect to mean time to failure (MTTF) characteristics and groups elements that are likely to experience technical advancement at the same rate.

In practice, DFLC is more often used to determine which elements should be kept separate than which elements should be combined. Elements that are technically stable should be kept separate from elements that will soon be replaced by new technologies and elements that have low failure rates should be kept separate from elements that fail frequently.

Design for Lifecycle goes hand-in-hand with Design for Disassembly. A product that disassembles easily will be disposed of, recycled, and upgraded more easily and at much less cost than one that does not. DFDA and DFLC are much more important now than in past when it was more common to simply dispose of the entire product than to upgrade it. Of course in a fast evolving consumer electronics market it is typical for multiple components to require upgrading at the same time. When coupled with products that are not designed at all for

disassembly (e.g., housings on tablets and smartphones that are glued together), one easily find modern products that are routinely thrown away rather than upgraded (Sreekumar, 2013).

In an odd kind of symmetry, the users of AT also experience life cycle changes over time. Interests and responsibilities may change, physical abilities may improve or degrade, support networks and family dynamics may change, and the best control site and method of control may change, all of which could require modifications or upgrades to a piece of AT (Simpson, 2010; Cook & Polgar, 2002). AT based on a modular architecture will support these changes better than one that is monolithic.

**Design for Standardization.** This X in Design for X goes without saying – and is not actually part of the Design for X lexicon – but no self-respecting architect or engineer would ignore national, international, or de facto standards when designing a product. Doing so would add tremendous costs to the product over its lifetime and limit the chance of producing a follow-on product. For example, no building architect would specify 3 inch by 5 inch lumber for the construction of the walls of a family residence. The requirement would have ramifications that extend beyond obtaining the necessary lumber to requiring a redesign of all windows, doors, and drywall. Appliance manufacturers would have difficulty developing appliances for such a home. As such, applying standards, where possible, is functionally equivalent to applying the heuristic to ensure openness in your architecture.

When creating designs for new technologies and markets it can be tempting to forge your own path. Certainly the manufacturer who establishes the market will often set the standard that others will have to follow. Such standards are called “de facto” which means something that simply “is” as a result of common practice. De facto standards can be just as powerful or even

more powerful than standards produced by official standards bodies because they represent the real state of the market and a base of widespread consumer investment.

There are few standards in the domain of control and communications AT. What standards are in use can usually be found on the border of the domain where the AT interfaces with common consumer products like computers, tablets and phones. There are no standards regarding the interfaces to humans themselves (control interfaces) or to the physical surroundings (e.g., mounting systems). Manufacturers often establish their own standards for how the products in their product lines will interface electrically and physically (e.g., the AbleNet Wireless standard and mounting standard for AbleNet devices). Proprietary standards, while guaranteeing success if used as directed, are often associated with more expensive solutions and have the effect of locking the customer into a single manufacturer's products.

One of the few consistent general standards for control devices is the use of a 1/8 inch (3.5 mm) plug and jack for low-power electrical connections. This paper will follow that standard and recommend the adoption of a de facto standard for mounting systems as well. The GoPro video camera has recently been enthusiastically embraced by the public. First by extreme athletes who wanted to document their accomplishments and then by the general public who wanted to add a video dimension to their blog or Facebook page. Mounting the small, light-weight camera has become a creative and prolific endeavor (Figure 3).





Figure 3. A small subset of the variety of commercially available GoPro camera mounts

At 100 to 250 grams, the GoPro camera has roughly the same mass as an AT switch and the same requirements for stability. Almost all GoPro mounting systems utilize a two fin to three fin adjustable joint (Figure 4) and a slide-in quick release base mount (Figure 5). This paper specifically calls out the use of the two fin joint on switch bases and recommends the

quick release slide be included at the base of the mounting system. Including these two features in the design of an AT device will greatly increase the mounting possibilities and lower costs.

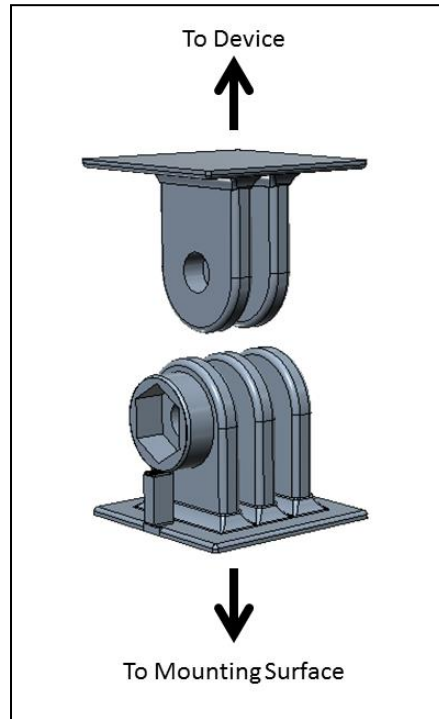


Figure 4. GoPro 2/3 Fin Adjustable Joint

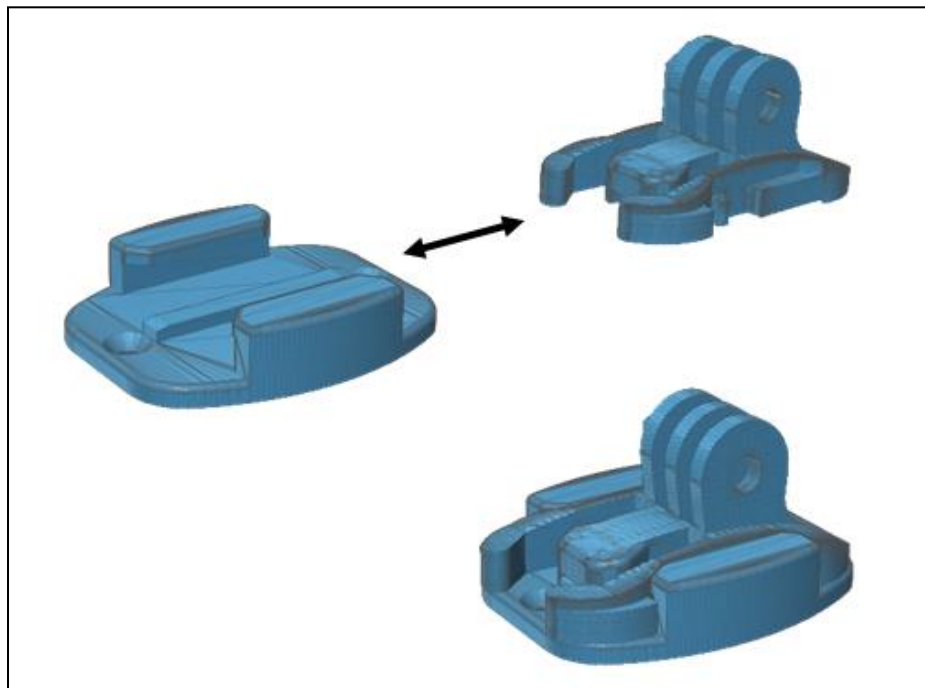


Figure 5. GoPro Quick Release Mounting System

## **Results and Discussion**

The following sections will describe control AT and communications AT in terms of the functions they provide and how those functions can be organized into modules. A rationale for that organization will be provided in terms of the Design for X criteria – in particular Design for Variety, Design for Innovation, and Design for Maintainability.

### **Control Assistive Technology**

“Control interfaces are the means by which the user interacts with any assistive technology. Examples include the joystick on a powered wheelchair, the keyboard on a computer, or the handle that operates the closing mechanism on a reacher” (Cook & Polgar, 2002, p. 7). The particular control interfaces that are the focus of this paper are commonly referred to as “switches”. They derive their name from their use in electrical circuits. As AT devices they serve to communicate the decisions of individuals with disabilities to other electrical devices which then act on behalf of the individual.

AT switches (simply “switches” going forward) come in a variety of forms that are directly driven by the way in which an individual will interact with them. Cook and Polgar (2002) define a control site as a point on the human body that can be used to activate a control interface or switch. Almost any part of the body, no matter how small, that is under conscious control, can be used to activate a switch. Figure 6 shows examples of switches that are activated in a different ways by different control sites.

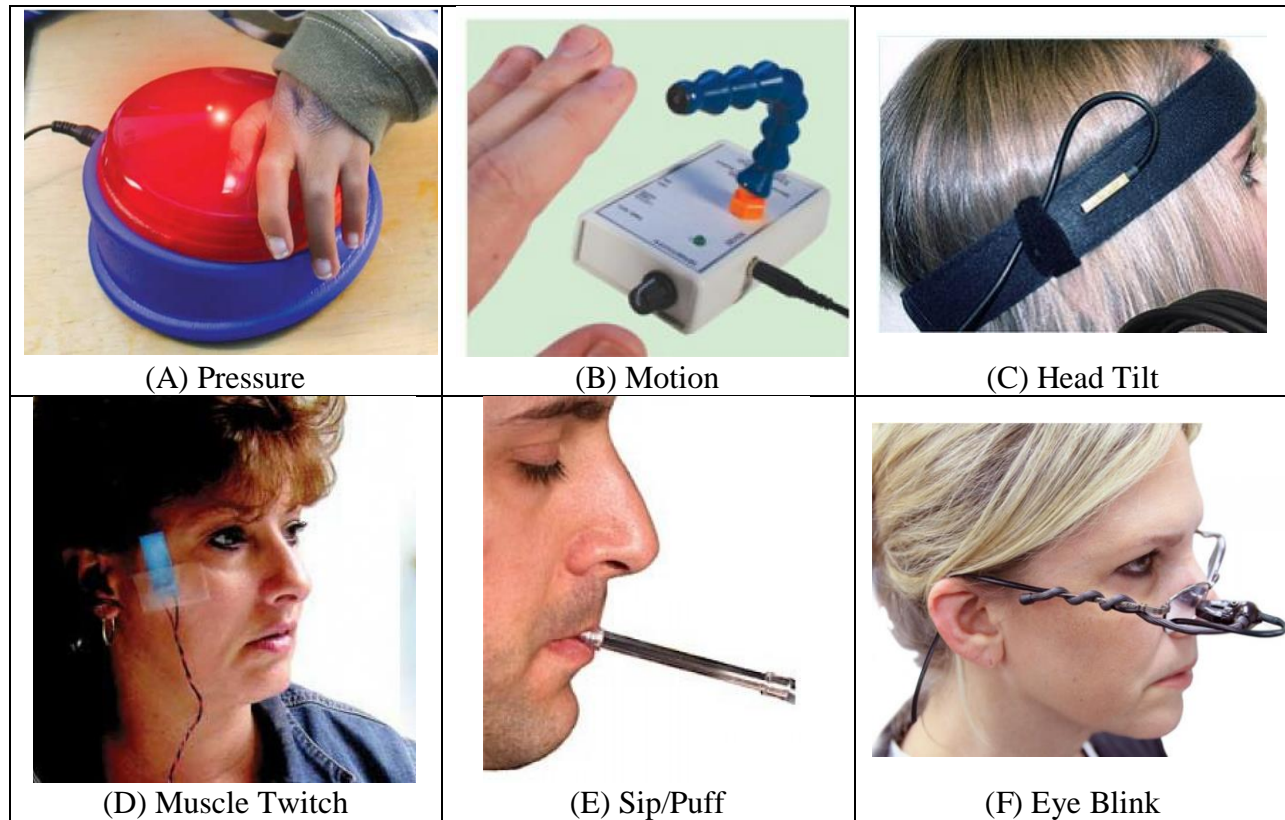


Figure 6. A few of the ways in which switches can be activated  
(images courtesy of the EnableMart website)

**Core functionality of a switch.** Switches provide the following core functions:

- Individuals interact with a surface or region of space to activate the switch.
- A normally open circuit is closed to indicate a choice or decision.
- Circuit closure is communicated to the affected system through a wired or wireless connection.
- When a wired connection is used the affected system normally provides power and current to the circuit.
- When a wireless connection is used the switch, itself, normally provides the power and current to the circuit.

- Feedback regarding successful circuit closure is provided in the through a combination of audible, visual and/or tactile information at the control interface and behavior at the affected system.
- The activation surface must be positioned within reach of the individual's control site through a mounting system.

**Additional/optional functionality of the control interface.** Switches may provide the following functionality:

- Signal Modification – The length of time the circuit remains closed may be extended without requiring the individual to continue to interact with the activation surface. This is referred to as a “latching” function.
- Signal Protocol Conversion – The signal may change format to meet the interface required by the controlled device. Common conversions include transforming the DC current to a wireless format (e.g., Bluetooth, IR, RF) and to a wired format (e.g., PC keyboard, Apple iOS Lightning Port)

**Switch types.** Cook and Polgar (2002) identify six different types of switches:

- Mechanical switches – activated by the application of force (examples: button, lever, wobble, joysticks, and membrane switches) – Figure 6, images A and C
- Electromagnetic switches – activated by the receipt of light or radio waves (examples: fiber optic and infrared switches as well as computer/brain interfaces) – Figure 6, image F
- Electrical Control switches – activated by electrical signals from the surface of the body (all capacitive switches) – Figure 6, image D

- Proximity switches – activated by a movement close to the detector but without actual contact – Figure 6, image B
- Pneumatic switches – activated by respiratory air flow or pressure (examples: sip/puff and grip switches) – Figure 6, image E
- Phonation switches – activated by sound or speech (example: “The Clapper”)

**Switch properties and their values.** Switches have a number of properties and each of those properties can have a number of values. The properties and values in Table A1 were collected from the EnableMart and AbleNet websites. All of these properties are options for custom assembly if properly modularized.

While some of these properties are dependent on other properties or collections of properties (for example, total weight will depend on button size and material as well as the presence or absence of batteries) the vast majority of these properties are completely independent. Additionally, it is reasonable to assume that a switch user might desire or require a value for each property independent of a value for another property. If we conservatively assume that there are a total of 15 independent properties and each of those properties has, on average, 4 possible values then there exist  $4^{15}$ , or one billion, possible switch configurations in this property space. No manufacturer could offer, nor could any distributor provide navigation through, this many options. One would need to whittle down the options to just those that individuals with disabilities actually need. Unfortunately, such a task is doomed from the outset. There is no single characterization of an individual with a disability – there are not even thousands. Each individual with a disability is truly unique. Note that this analysis only takes into account the physical characteristics of the switch. What about the aesthetic ones? Other than the color of the button (for which only a few options are typically provided), the design of

switches suffers from all of the issues that were raised earlier regarding industrial aesthetics. An effort to support all the aesthetic options that users might desire would result in an option-explosion that would be completely unmanageable.

**A modular architecture for control assistive technology.** As stated, the primary goals that drive this particular modularization are: variability/customizability, innovation, and maintainability. If an element of a switch might need to vary for purposes of customization, allow for innovation, or require maintenance independently of other elements, then it was placed in a separate module. Figure 7 presents this modular architecture:

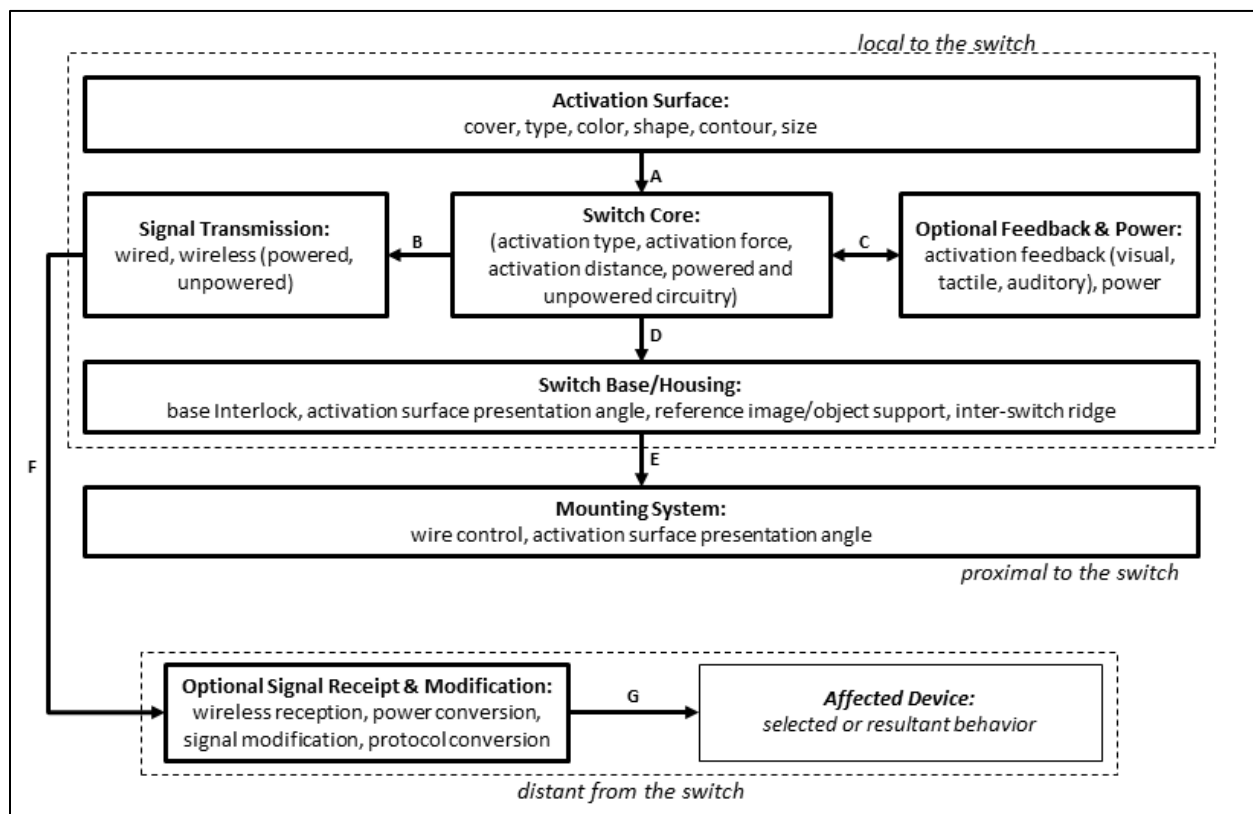


Figure 7. Modular Switch Architecture

*Module and interface descriptions.*

Modules:

- **Activation Surface** – The activation surface provides a target for the user's control site. The activation surface may be accompanied by a cover that is sized to fit the surface. The activation surface is a target for massive variability and aesthetic design.
- **Switch Core** – The switch core is largely invisible to the user and provides two circuits that are closed simultaneously when the activation surface is sufficiently manipulated. Switch cores may come in multiple flavors depending on the type of switch – primarily whether it is mechanical or electronic. The switch core contains a normally open, physical or virtual, double pole single throw (DPST) switch that closes the powered and unpowered circuits in unison (see Figure 8 for a description of the circuit wiring). The switch core provides ports to allow external elements (i.e., the signal transmission and feedback/power elements) to access the internal circuits. Finally, the switch core provides manual adjustments to configure the activation distance, pressure, and range (for proximity style switches).
- **Signal Transmission** – The signal transmission module provides options for wired and wireless connectivity between the switch core. The options for wireless transmission might include Bluetooth, IR, RF or some entirely new protocol. A wired option is as simple as a set of stereo audio cables. Note that only the monaural feature of the cables would be utilized. It is unclear whether the Bluetooth option would sit on the powered or the unpowered circuit.



Bluetooth requires a lengthy set-up/pairing period during which a Bluetooth component would need to be powered independent of other activity within the switch.

- **Optional Feedback and Power** – The feedback and power modules provide either power to the powered circuit of the switch core or sensory feedback to the user that the switch has been activated and the circuits have been closed. It is assumed that the sensory feedback components require power so they have been placed on the powered circuit and will require that a power/battery component also exist on the circuit in order to function.
- **Switch Base/Housing** – The switch base/housing component protects the connection points of the switch to the transmission and behavior components. It also provides an industry standard mounting point that connects the switch core and activation surface to the switch mounting system as well as inter-switch features in the event that the user creates a multi-switch configuration. The switch base/housing may have capabilities for adjusting the presentation angle of the activation surface in multi-switch configurations but it is believed that this function is best performed by the mounting system. Finally, the switch base/housing needs to support a variety of configurations depending on the choice of activation surface and mounting system.
- **Mounting System** – The mounting system is not part of the switch itself but is critical to locating and orienting the activation surface so as to take advantage of the user's control sites to the greatest extent possible. This includes activation surface presentation angle and multi-switch orientation. In the event that the

switch is utilizing wired transmission, the mounting system has responsibility for wire management. Optimally, all wiring would be contained within the mounting system itself.

- **Optional Signal Receipt and Modification** – When the switch uses wireless signaling, a signal reception component must be included. This component can be a separate module or integrated with the “affected device” (e.g., the Bluetooth reception capability of the iOS operating system). Following the wireless reception component or following the switch core in a wired configuration would be the optional component to modify the duration of the signal (e.g., a latching feature). Last in the path would come any protocol or voltage conversion components.

Interfaces:

- **A** – The activation surface mechanically attaches to the switch core in a manner that can easily be disassembled so that a different activation surface can be substituted.
- **B** – The switch core communicates a circuit closure to the signal transmission module. The communication may be accompanied by power if the signal transmission module is associated with the powered circuit of the switch core.
- **C** – The switch core provides power via a switch closure to visual, tactile, and/or auditory components to provide sensory feedback to the user that the switch has been activated. All listed components reside on the powered circuit of the switch core.

- **D** – The switch core mechanically attaches to the switch base/housing in a manner that can easily be disconnected to provide access to the switch core and transmission/power/feedback components for maintenance and configuration purposes.
- **F** – The signal transmission component is physically or wirelessly connected to a wireless receiver (in the case of wireless transmission) and/or optional signal modification components on the way to the affected device.
- **G** – The optional signal receipt and modification components can be connected to the affected device in a wired or wireless manner depending on the nature of the affected device and the type of signal modification that has taken place, if any.

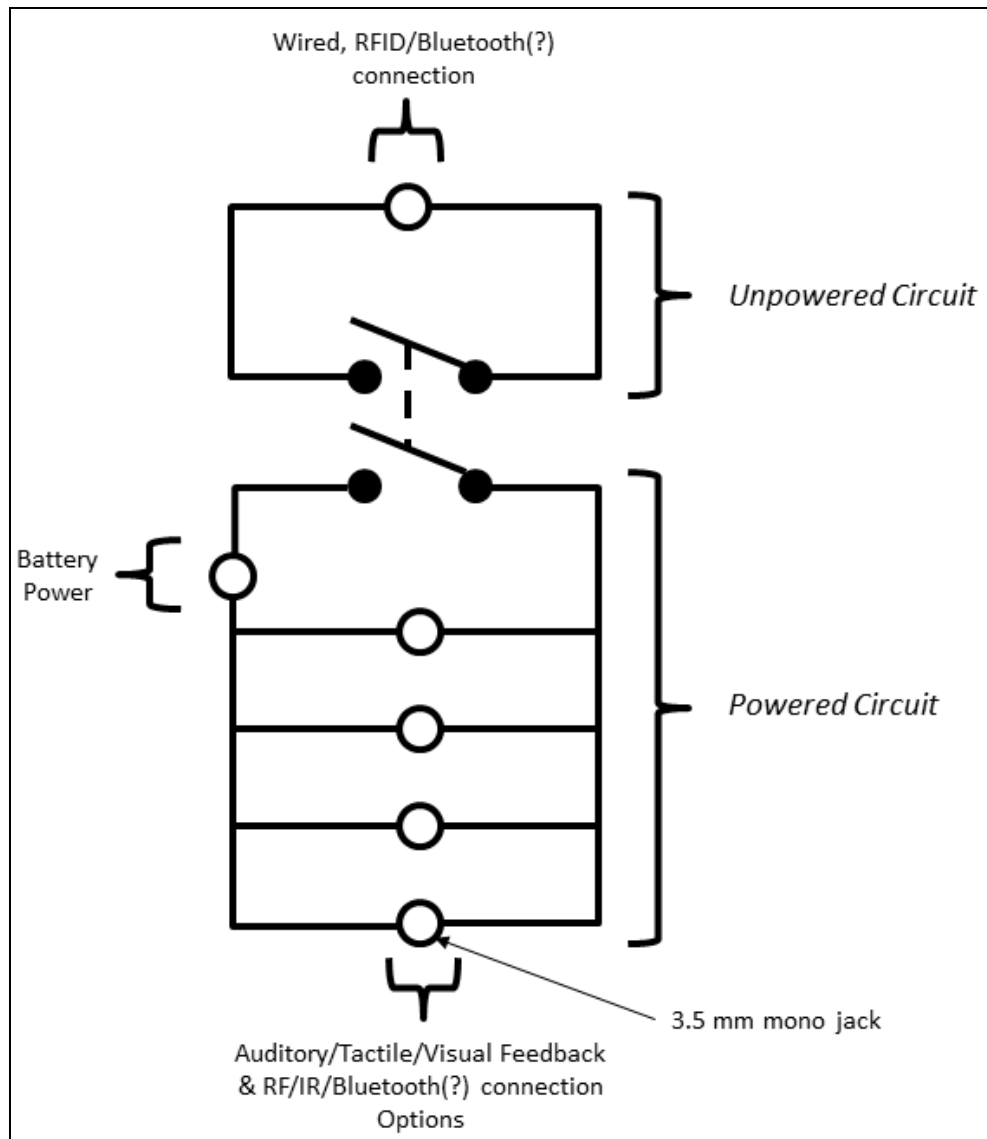


Figure 8. Internal wiring of the switch core module including the dual circuits and DPST switch

**Key characteristics of this modular organization.** This organization of modules emphasizes customization and configuration. The activation surface is not integral to the switch core and can easily be replaced with a different, more easily activated and/or more aesthetically pleasing version. The feedback components are easily configured based on the needs and preferences of the user. Activation pressure, distance and range are completely adjustable based again on the needs and preferences of the user. The switch base/housing is designed to

accommodate a variety of standard mounting systems. The transmission method used by the switch is simple to configure and can accommodate new wireless transmission methods as they come along, including, low-power Bluetooth and a no power, RFID-based method. Finally, all components can be assembled through manual screw-on or manual snap-on/snap-in methods to make configuration/customization and maintenance quick and easy.

**Visualizing the modules.** Figure 9 presents a conceptual but physical instantiation of the proposed control architecture in the form of a simple mechanical, button-style, pressure switch.

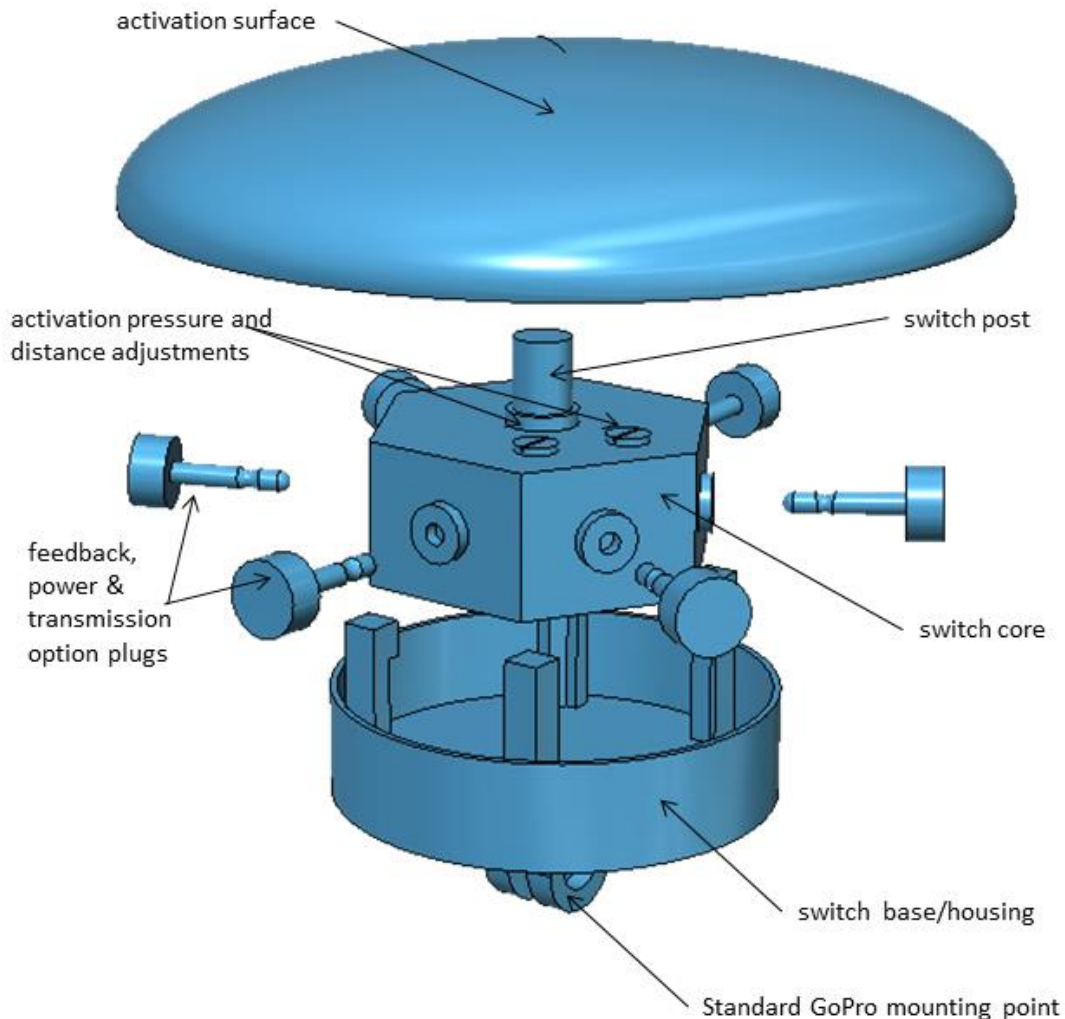







Figure 9. A conceptual instantiation of the proposed modular switch architecture

*Examples of current products that embody aspects of this modularization.* There are a few switch products and accessories that embody elements of the proposed architecture. They fall into two groups: those that support swapping activation surfaces, external signal modifiers and protocol converters, and one example of a switch housing that provides an adjustable presentation angle for the activation surface. Table 1 provides examples of these switches and accessories.

Item Name	Item Image	Feature
AbleNet Jelly Bean Twist Switch		Swappable activation surfaces though the color choice is underwhelming
Gumball Switch Textured Overlay Set		Activation surface covers with a variety of textures
Adjustable Pressure Saucer Switch		Activation pressure can be adjusted from 1/2 to 32 ounces, also the only switch discovered exhibiting a second-order convex surface
Adjustable Angle Switch		User adjustable angle of presentation of the activation surface from 32 to 90 degrees. (It is difficult to tell but the 1/8" jack on the right surface of the housing may support an external wiring plug.)
Switch Modifier (Model 605) by Enabling Devices		Does only one thing and that is to control the duration of the switch signal



Item Name	Item Image	Feature
USB Switch Interface		Performs protocol conversion from switch circuit closure to a PC keyboard keystroke via a USB interface
Inclusive Click-On 2		Switch circuit closure to 110v converter. Also performs signal latching and extended duration functions.

Table 1: Examples of switches and accessories showing aspects of the proposed architecture (photos courtesy of the EnableMart and AbleNet websites)

## Communications Assistive Technology

This section will address the architecture of simple speech generating devices (SGDs). Speech generating devices are a subset of augmentative and alternative communication (AAC) devices. Figure 10 presents a sampling of products that are used by individuals with disabilities to communicate simple words, phrases and sentences. Switches are a core component of these devices, so much of the modular architecture proposed above will be applicable here as well. While particular features of the products differ (e.g., number of switches, number of messages, order of message playback, types of external inputs/outputs) their usage is very similar:

1. The device is placed in record mode,
2. A level position and/or switch button is specified,
3. A voice message is recorded and stored in association with the specified switch and level position,
4. The process is repeated for all remaining voice storage locations and/or switches,
5. The device is placed in playback mode,
6. A level position is selected

7. A switch button is pressed
8. The recorded message for that level position and switch is retrieved and played back through a speaker.
9. Depending on features of the device, a second press of the switch button could result in the same message being spoken a second time or the next message in the sequence being spoken.





Figure 10. Examples of simple speech generation devices

Manufacturers of these devices make many design choices around property values and then bake those choices into the SGD. Why are there three switches in the case of the device show in Figure 10, image E while only two switches in the case of the device in image D; why an inter-switch ridge on the face of the latter device but not the former; and why are both devices

presenting their activation surfaces at a 45 degree angle while the device in image A is presented horizontally? I am sure that each manufacturer had reasons for their choices, but each manufacturer has limited the usefulness of their product by using static implementations. Yet, these products have more significant issues than their fixed number of switches or their presentation angles.

Note that all of these devices incorporate mechanical, pressure switches. To utilize a different activation method, the SGD has to provide external switch inputs and the alternative switches have to be connected to the SGD via those inputs. Fortunately, almost all SGDs include ports on their housings for connecting external switches – one external switch port for each integrated switch. This is a recognition that it is unlikely that the fixed property values associated with the integrated switch will match the high variability in capabilities of individuals with disabilities. But if the integrated switches must be bypassed in order to make the device functional in many cases, what is the value of the integrated switches (which can contribute up to 50% of the cost of the device)? In that case, the SGD is little more than a box that supports recording, storage, and playback of messages. The stimulus to play a message would take place outside of the SGD.

These simple SGDs support minimal message storage. To a degree, that is a function of the limited electronic memory on board the device, but it is also a function of the user interface. A mechanical “level” slider switch can be placed in any one of up to three positions. The current position determines which message (or sequential set of messages) will be played when the user presses the switch. Three levels and two switches means that the user has access to six messages. The fact that the level slider is small and requires significant dexterity to manipulate means that individuals with significant motor limitations will have to rely on a caregiver to

change the position and enable access to the additional recordings. The manufacturer usually describes the purpose of the levels to represent different messaging needs at different times of day (morning, afternoon, and evening) or different locations (home, school, community). Viewed in this context, simple speech generating devices provide their users with only a minimal communication ability (e.g., only two phrases that can be spoken in the morning each day) combined with the lack of independence associated with requiring the involvement of a caregiver to select the appropriate level.

All simple SGDs include an integrated microphone and speaker. The quality of the generated voice message will depend significantly on the quality of that microphone and speaker. Some SGDs provide a microphone port for optional use of an external microphone which will enhance the quality of the recorded message and some SGDs provide a speaker port for connection to a high quality speaker which also will enhance the quality of the playback. But again, if the recording and sound production functions of the SGD are also “farmed out” to third party products, the functionality of the SGD is reduced to just storage, selection, and delivery of recorded messages.

A particular issue with all SGDs is the location of the integral speaker – within the SGD itself. In his design of an AAC device for the students at Portland College, Allen (2005) discovered several advantages of separating the speaker from the other components of the AAC device.

Having a separate unit producing the final audio output offers a number of alternative ways of using that output. The user may wear the unit in such a position that the voice sounds as though it is coming from the user, or the user may pass the unit to the conversation partner so that a more intimate conversation may ensue. In either event the

integral digital volume control is close at hand allowing the unit to produce anything from a respectable shout to a whisper. (p. 142)

To illustrate his point, Allen recounts a case where the speaker was handed to a caregiver when the individual with a disability was using the toilet. When finished, the individual was able to privately notify the caregiver that their help was needed again.

The SGD speaks for the user because the user cannot speak for themselves. That exposes an inherent problem for these devices...Who's voice should be recorded? Commonly, the messages in simple SGDs are voiced by a family member or caregiver. This can create an odd situation where a young boy uses his SGD to request an item or respond to a question at school and what comes out of the device is the voice of the boy's mother or teacher. It may be possible to minimize this conversational "shock" by having another child of about the same age and gender record the messages. Unfortunately, this arrangement can be difficult to sustain and coordinate going forward.

An alternative solution to digital recording of voice messages is computer synthesized speech. Digital recording stores a digital representation of the recording in electronic memory. Just a few seconds of speech can require large amounts of memory for storage depending on the compression algorithm that is used (Cook & Polgar, 2002). Synthesized speech uses complex algorithms to generate speech on the fly from a stored textual representation which requires almost no memory, but does require significant processing power.

While the technology to produce synthesized speech was primitive just a decade ago, current algorithms can produce amazingly realistic speech including gender, age, and locale variations. All sophisticated AAC devices utilize synthesized speech. Most smart devices now offer speech generation built into the operating system that can produce realistic text to speech.

Unfortunately, simple SGDs are not smart devices. However, it is possible to insert smart technologies into the modular architecture of the SGD and thereby leverage speech technologies.

**Core functionality of a Simple Speech Generating Device.** SGDs provide the following core functions:

- << **All of the control interface functions** >>
- Recorded voice storage location identification.
- Word or phrase recorded via an internal microphone or an external microphone and stored local to the SGD.
- Word or phrase is chosen through settings, control interface location, and selection logic.
- Volume control for speech playback decibel level.
- Internally wired, externally wired, or wireless communication with speaker.
- Word or phrase picture/object is provided for training or to facilitate switch selection.

**Additional/optional functionality of a Simple Speech Generating Device.** SGDs may provide the following functionality:

- Pressing the switch activates an external device or toy simultaneous with the playback of the recorded voice message.
- Each press of the switch plays a randomly selected message from the sequential message set (for game play).

**Simple speech generating device properties and their values.** SGDs have a number of properties and each of those properties can have a number of values. The properties and values

in Table A2 were collected from the EnableMart and AbleNet websites. All of these properties are options for custom assembly if properly modularized.

**Extending the modular architecture to simple speech generating devices.** The modular architecture of an SGD (Figure 11) extends the switch architecture, and so, begins with that architecture (“N” instantiations the switch architecture depending on the needs and cognitive capabilities of the user). Instead of the switch or switches sending their signal to a signal modification module, they control a message server and the affected device from the switch architecture is instantiated as a wired or wireless speaker.

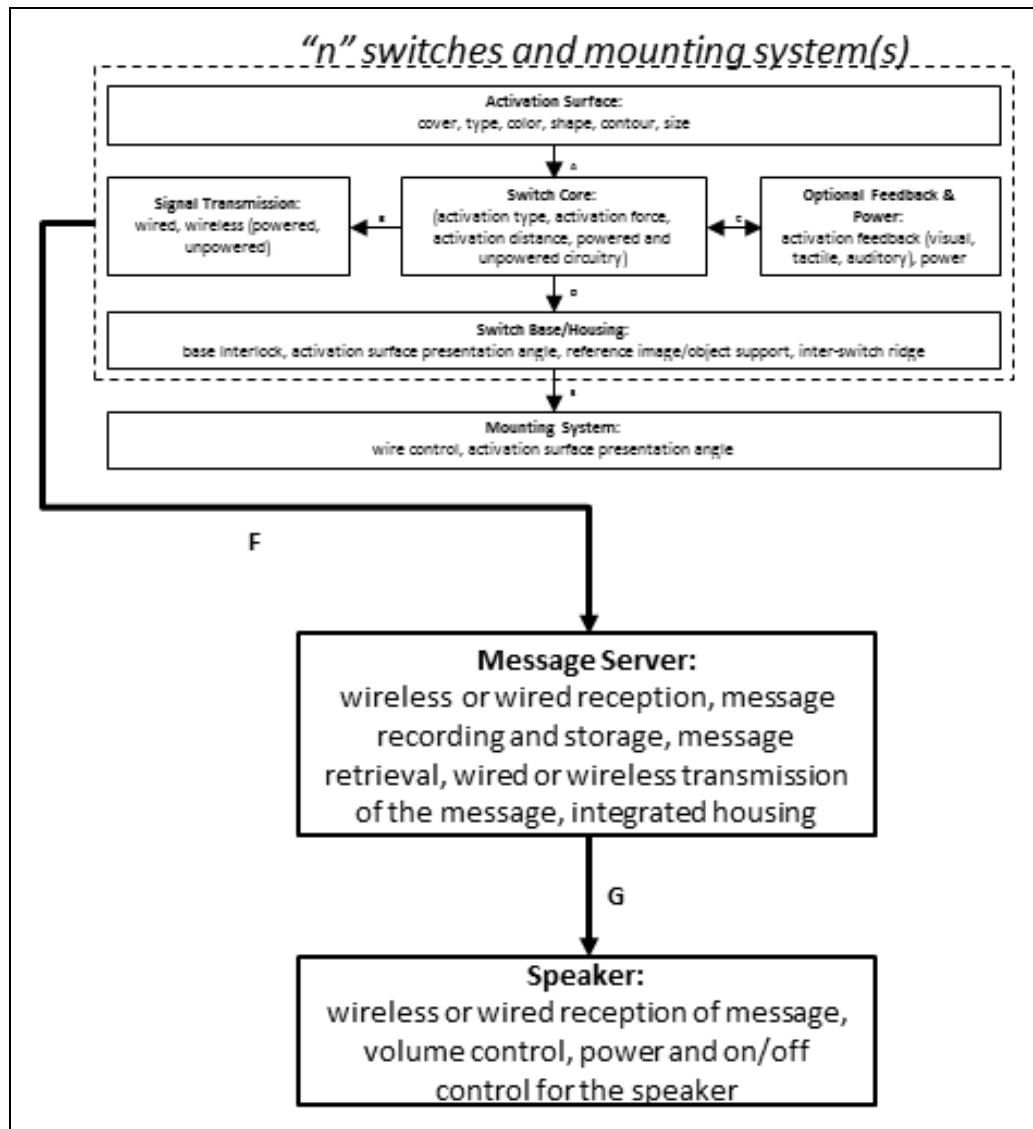


Figure 11. Modular SGD Architecture

***Module and interface descriptions.***

Modules:

- **Switch** – The description of this module is unchanged from that in the modular switch architecture. There may, however, be less of a likelihood of an audible feedback component since the message playback could serve the same purpose.
- **Mounting System** – The description of this entity is unchanged from that in the modular switch architecture.

- **Message Server** – The message server provides digital message recording, storage, selection, and delivery of messages. Any sound can be stored and retrieved but the server is most commonly used for voice messages. The server accepts digital signals via a number of input interfaces. Those signals may represent sound (via an external microphone) or circuit closures (via a connected switch). Logic associated with each of the input ports determines the behavior of the server in response to a received signal. The server has an internal source of power and may support the receipt and transmission of wireless data.
- **Speaker** – The speaker provides audible playback of digitally received data. The speaker provides output volume control and has its own internal source of power. The speaker may support wired or wireless input signals, or both.

Interfaces:

- **A through E** – The description of these interfaces is unchanged from that in the modular switch architecture.
- **F** – The signal transmission component is connected physically (wired) to an input port or wirelessly to internal circuitry on the message server. Configuration of that port or circuit determines what the server does upon receipt of the signal.
- **G** – An output port on the message server is connected physically (wired) to an input port or wirelessly to internal circuitry on the speaker.

***Key characteristics of this modular organization.*** This organization of modules emphasizes configuration of the device. It recognizes that the switching interface is likely to be highly varied from individual to individual and retains that functionality in a separate set of modules. It also recognizes significant value in separating the speaker from the rest of the



devices for reasons described above, and so sets aside a separate module for that functionality. Lastly, by placing configuration at the port level it can be possible for one switch to control the effect that other switches have on the behavior of the message server. Specifically, it allows one switch to affect the storage locations associated with other switches and give the user the ability to choose the current level associated with a switch without requiring intervention of a caregiver to manipulate a small slider switch on the server (the equivalent of choosing a “level” via the slider switch on the housing of a traditional SGD).

**Visualizing the modules.** Figure 12 presents a conceptual but physical instantiation of the proposed SGD architecture in the form of a simple message server and simple speaker.

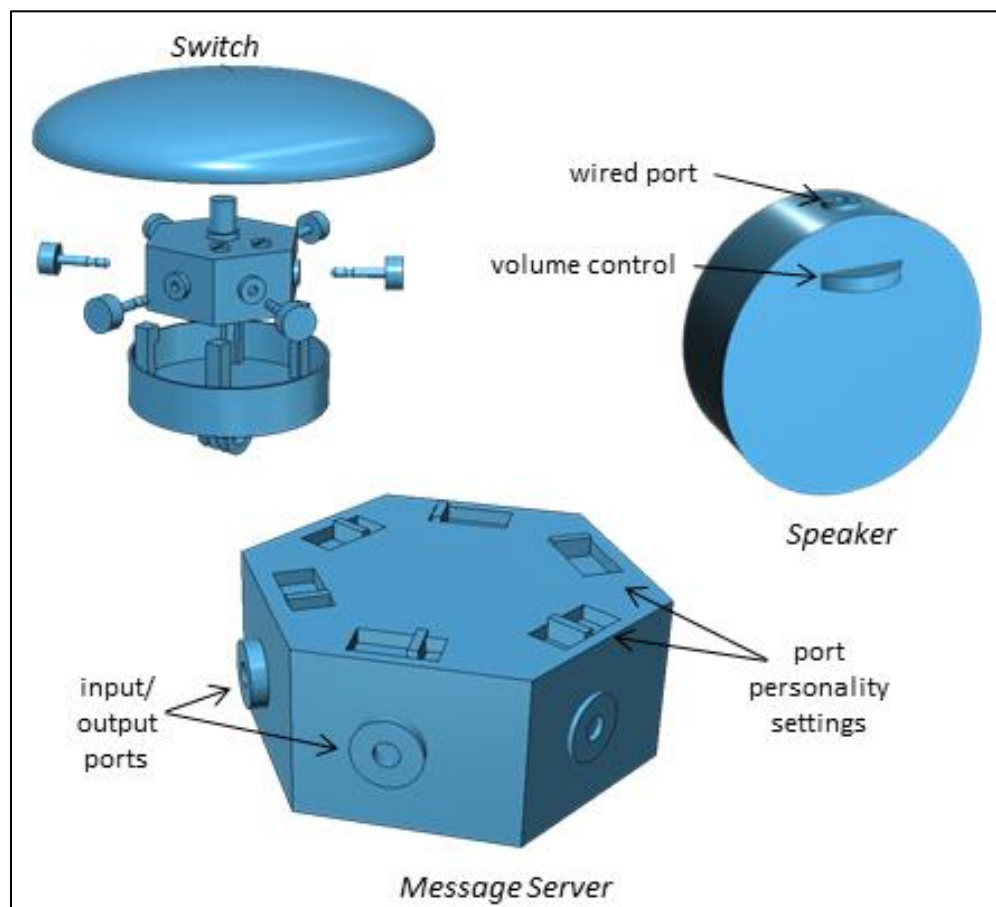


Figure 12. A conceptual instantiation of the proposed modular SGD architecture

There are a few items of note in this conceptual image. First, the switch component is completely unchanged and continues to support wired or wireless transmission to the message server. The message server is completely dedicated to collecting, storing, retrieving, and delivering messages. A number of standard, monaural 3.5 mm ports are arranged around the outside of the housing. These ports can be used for input (connected to a switch or a microphone) or output (wired speaker) depending on the position of the personality setting slider for that port. It is possible that pluggable wireless transmission and reception components could be created (similar to the wireless transmission component of the switch architecture), which would mean that the server would not have to be responsible for that functionality. In that case the personality slider would be used to indicate those additional intentions for the port. The message server is contained in a sealed housing to protect the internal, integrated circuitry. The housing has no special support for mounting because the message server is assumed not to have special mounting requirements and, in fact, is likely to be stored out of sight of the user and the public.

With sufficient internal logic, the switch connected to one port could control the behavior of a port associated with another switch. For example, one port could be used to redirect the message location associated with another port. In that way, the SGD user could use a switch to change the level setting for one or more other switches and thereby not require that that action be done by their caregiver.

***Examples of current products that embody aspects of this modularization.*** There are a few commercial and two AT distributed products that embody elements of the proposed architecture (Table 2). First there are many commercially available wired and wireless small

speakers. In addition, EnableMart offers a product called the CheapTalk Switch Module that has an eerie resemblance to the proposed message server module combined with the speaker module.




Item Name	Item Image	Feature
JS Portable Mini Wireless Bluetooth Nut Speaker with Sling		Bluetooth connectivity and clever design but, unfortunately, no integrated volume control. (\$16)
Mobility AquaPlay Waterproof Bluetooth Speaker		Bluetooth or wired connectivity, integrated volume control, carabiner or suction cup mounts included. (\$11)
Voombox-Travel Wearable Speaker		Bluetooth connectivity. Because it is sold by AbleNet in the context of AT it is priced at \$95, but it is no different and no better than the speakers above at 1/8 <sup>th</sup> the price.
Cheap Talk Switch Module		Does not attempt to integrate the switches though it does integrate the speaker. For \$106 this item provides messaging for up to 4 switches – functionality for which other monolithic product manufacturers charge as much as \$430.

Table 2. Examples of items that embody aspects of the proposed simple SGD architecture (images courtesy of the Amazon and EnableMart websites)

## **Examples of Innovation and Customization Made Possible as a Result of the Proposed Modularization**

*A picture is worth a thousand words. Chinese Proverb. 1000 BC*

*One insight is worth a thousand analyses. Charles Sooter, April 1993*

(Maier & Rechtin, 2002, p. 17)

Formalizing modules and their interfaces is a critical part of modular decomposition. In order to accommodate changes in associated modules, it is often necessary to generalize (and standardize) the interface as much as possible. In the process of creating a general interface for switch communication with downstream modules, the author had an insight about the benefits of separating the wire from the switch in a wired switch configuration. Next, rather than recommending that each switch be powered in order to support wireless communication, the author had an insight about non-powered wireless transmission (at least from the point of view of the switch). Also, mulling over the market issues for AT manufacturers, especially the issue that highly specialized and varied customer needs result in small batch sizes which result in high manufacturing costs, the author was reminded about a recent trend in the industry called Rapid Manufacturing/Prototyping built around 3D Printing. Finally, stripping the switch, the speaker and the microphone from the simple SGD, left the author thinking about what it would take to leverage commercial technology to provide the functionality at the heart of a simple SGD. This section will describe in greater detail each of these insights that came about as a result of the proposed modular architecture, and how they can benefit individuals with disabilities.

### **Flexible transmission.**

*Improving the wired connection.* Almost all switch manufacturers provide a cord that passes directly through the housing of the switch unmodified. When not in use, these cords are

commonly wrapped around the switch to keep them from tangling with other equipment (Figure 13).



Figure 13. Typical switch cord design and storage

The red arrow in the image on the left shows where the soft wire leaves the hard switch housing. When the cord is wrapped around the switch this area of the cord will inevitably be pulled tightly against the hard surface of the housing and turned at a right angle to its normal orientation. The edge of the hole where the cord exits the housing is usually sharp forcing a sharp turn by the cord. This action produces significant stress on the soft copper conductors inside the plastic sheathing. With repeated wrapping and unwrapping, the copper conductor will begin to fracture – a process called “fatiguing the metal”. Eventually, the conductor will separate and the connection will either fail entirely or will fail only intermittently and seemingly at random. Better designed switches add a feature to the cord called a “strain relief” – visible in Figure 14 – both at the switch end of the cord and at the plug end (which is already quite common) to reduce this tendency of the conductors to fracture when twisted.

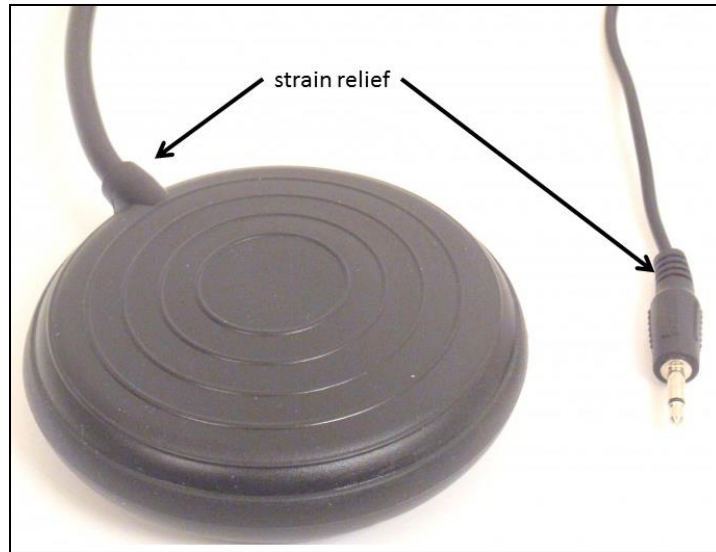


Figure 14. Use of a Strain Relief

The architectures proposed for both switch signal transmission and on the interface between the message server and the speaker make no assumptions about whether the interface will be wired or wireless. As a result, each end of the wired interface is just a 3.5 mm monaural jack. A search of CablesToGo.com for “3.5mm male to male audio cables” produces the result below in Figure 15.



Figure 15. Male to Male Stereo Audio Cables  
(image courtesy of the CablesToGo website)

The cables are available in a variety of lengths from 1.5 feet to 50 feet, at prices from \$4.50 to \$20.00 each. Both plugs have strain relief features. Note that stereo plugs and cables can be used transparently with monaural jacks and their associated circuits. So besides the built in strain relief at each end, these cables can be purchased in a length that is specific to the mounting needs of the switch or speaker and can tolerate being wrapped around the switch – or can easily be disconnected for use in another setting where the original switch is not a good fit.

*A new kind of wireless transmission.* To adhere to the proposed modular architecture for SGDs and provide the same functionality as a four button product would require mounting four independent switches for the user. In itself, this is not an absurd idea in that it might be much easier for the user to communicate through four independent control sites than to force the user to develop the range and accuracy in one control site to reliably activate four switches residing in the same housing. Still, four switches means four wires that have to be routed and managed.

The obvious solution would be to use wireless switches, but they bring their own headaches. The first headache is cost. Bluetooth, IR, and RF transmission components are powerful transmission protocols and they carry significant costs to add to a product. In reality, they are too powerful for this purpose. At 24 Mbps, the data bandwidth for Bluetooth is theoretically wide enough to carry a video signal. A switch has a very narrow signal. The circuit is just “open” or “closed” and that one bit of information changes at a very slow rate – about once or twice a minute for a simple SGD. Bluetooth is overkill. There is also the cost and maintenance burden of purchasing and replacing the batteries that drive these power-hungry technologies.

The question then comes to mind: “is it possible to provide wireless transmission with low- or no-power requirements?” One possibility might be RFID technology. RFID technology

is ubiquitous. It is used to automatically monitor the progress of items through manufacturing or delivery processes. The technology is comprised of two components. An RFID tag that is attached to the item of interest and an RFID reader that is constantly sending out a signal looking for any tag. The tag is composed of a chip connected to an antenna (Figure 16). When a tag comes within range of the reader's signal, the signal is picked up by the antenna in the tag which sends power to the chip. The chip then broadcasts its ID using the power of the reader's signal. The RFID tag contains and needs no internal power.

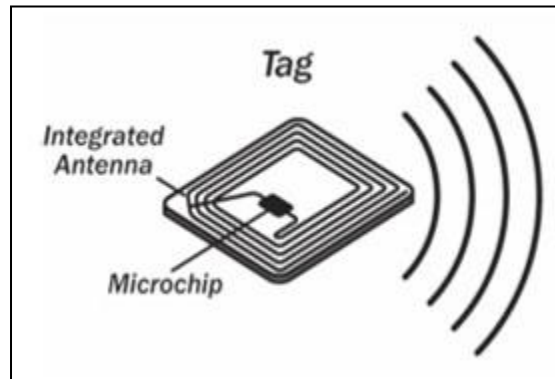


Figure 16. The Structure of an RFID Tag

RFID readers are proximity sensors meaning that the tag has to come within range of the sensor. So how would a proximity technology be modified to represent circuit closure in a switch? The answer could be in the relationship between the chip and its antenna in the RFID tag. In order to generate a return signal, the RFID chip must receive a signal from the reader via the antenna. The idea would be to plug the RFID tag, re-formed as a switch option plug, into the non-powered circuit inside the switch core. Closure of that circuit would complete the connection between the antenna and the chip within the tag and the chip would immediately begin broadcasting its ID. It is notable that the ID is up to 96 bits in length, meaning that it could have approximately  $2^{96} = 8 \times 10^{28}$  values. This is almost twice as large as the number of grains



of sand on the surface of the earth – squared (i.e., more than enough for this purpose). Another item of note is that RFID tags are routinely printed at pennies per tag making this an extremely cost effective technology.

Each time the switch were activated, the RFID tag would suddenly appear as present to the RFID reader, which would pass that information on to a processor that mapped the tag's ID to a function. When the switch was released, the RFID tag would disappear and the reader would pass that information on as well. The only component in this system that would need to be powered would be the RFID reader which could be mounted somewhere near the individual with a disability – for example, on their wheelchair, and drawing power from the wheelchair battery.

**Design for Makers (DFM).** An architecture that supports variation and customization does not, by itself, guarantee that the variety in options will be produced. The pressure still exists for manufacturers to mass produce their products to the greatest extent possible and mass production is the enemy of variety. For AT manufacturers, there is pressure to treat even their small market as uniform so that they can utilize bulk production methods as much as possible. Cook and Polgar (2002) relate production size to functionality as well as cost:

First, there is the direct relationship between cost and volume of production, which is why certain low-tech devices such as mouth sticks may cost in the hundreds of dollars and a high-tech electronic calculator costs less than \$20.

Second, the difference between devices produced in large volumes and those produced in smaller volumes is sometimes reflected in overall sophistication and capability rather than directly in price. For example, a personal computer that is capable of performing a wide variety of tasks and that uses sophisticated and

complex components is often comparable in price to a much less sophisticated but more specialized assistive device. Thus more function for the price is often gained when a device is produced in larger quantities. (p. 23)

Batch size also impacts the rate of innovation. According to Borisoff (2010), “Manufacturing a new product requires new tooling, processes, and training for the supplier. These costs are somewhat (though not entirely) fixed regardless of volume size, thus putting a greater burden on companies with only low volume sales projections” (p. 107).

In that case, AT devices will always have a higher price, less functionality, and less innovation than products produced for the general public. That is unless manufacturing techniques can be utilized that remove the economic advantage of mass production. Rapid Manufacturing/Prototyping may be that breakthrough.

***Rapid manufacturing/prototyping.*** Rapid manufacturing (RM) is defined as the use computer aided design (CAD) tools to produce instructions that will directly drive computer numerical control (CNC) machines, which use an additive manufacturing process to create objects that can be used directly as finished products or finished components (AlGeddawy & ElMaraghy, 2012). Additive manufacturing generally works by creating objects in 3 dimensions by adding layer after layer to the object either from top to bottom or from bottom to top. The machines that perform the work look and act like printers so the process is often referred to as 3D printing.

Current additive manufacturing processes can work with a variety of materials from plastics to resins to metals at both industrial and personal scales. The most ubiquitous version of additive manufacturing is fused deposit modeling (FDM) and the most ubiquitous materials used in FDM, because of their low cost, are polylactic acid (PLA) and acrylonitrile butadiene styrene

(ABS) plastic. 3D FDM printers extrude heated filaments from a heated nozzle that harden as they cool. The filament is laid down in fine layers and can take hours to produce a final product, but the printer is general purpose, and based on the instructions it is given it can produce an entirely different product with each run with no retooling costs (Figure 17). 3D printing is the ideal manufacturing technique for small batch production in support of small markets with high variability in needs (i.e., the market for AT).

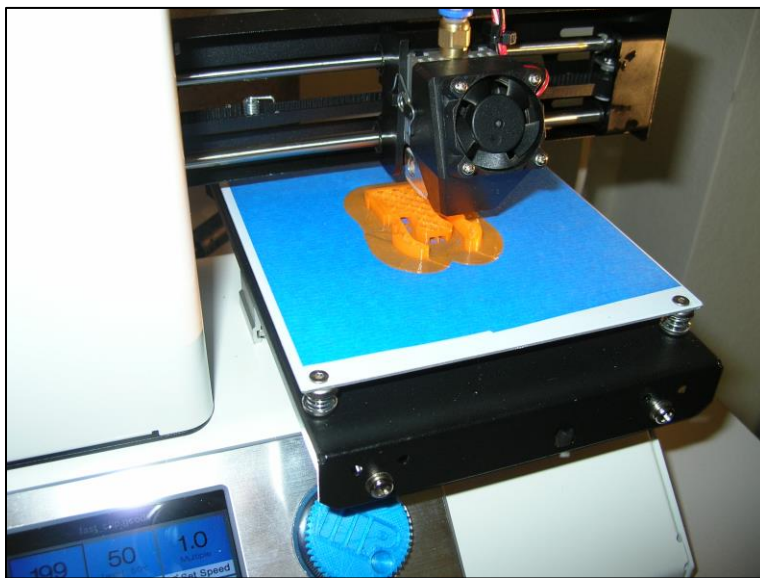

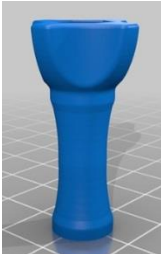


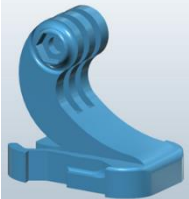


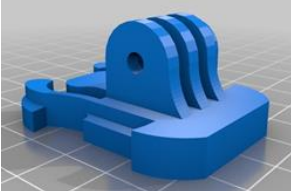



Figure 17. A low cost 3D printer creating a part by FDM using plastic filament

***Makers, crowd-sourcing of design, and 3D printing.*** With the introduction of low cost (less than \$500) 3D FDM printers, a tight-knit community of technologists has grown up around the design and production of 3D objects. These individuals are affectionately known as “Makers” because of their commitment to producing creative and useful real-world objects. The community is dedicated to sharing with each other and learning from each other. Objects are designed in a CAD tool by one individual and then shared with anyone interested in that object. The object is normally offered for free, licensed under the Creative Commons, often requiring only that the creator be acknowledged somehow. The primary vehicle for sharing 3D designs is

the website Thingiverse. Thingiverse claims to contain over 750 thousand 3D models with hundreds more being uploaded every day.

Many components of the switch and SGD modular architectures can be manufactured from PLA or ABS plastic using a 3D printer - primarily the activation surface, switch housing, and mounting system. The author experimented with several of these components to validate feasibility and to compare the cost of components that have been 3D printed versus those that are produced via large scale, injection molding techniques and sold commercially to the general public. In particular, the author explored the availability of GoPro mounting system component model designs on the Thingiverse website and the cost of their production. Table 3 shows the selected, commercially available, mounting component, its model equivalent on Thingiverse, the 3D printed object, and the relative costs to purchase commercially or produce using FDM.

GoPro Mounting Accessory	Thingiverse 3D Model	3D Printout	Relative Cost
			<u>Commercial:</u> \$2.40 <u>3D Printed:</u> PLA 5¢ hardware 50¢
			<u>Commercial:</u> \$4.00 <u>3D Printed:</u> PLA 5¢ hardware 20¢
			<u>Commercial:</u> \$4.00 <u>3D Printed:</u> PLA 15¢ hardware 20¢



			<u>Commercial:</u> \$3.00 <u>3D Printed:</u> PLA 15¢
			<u>Commercial:</u> \$8.75 <u>3D Printed:</u> PLA 20¢ hardware 50¢
			<u>Commercial:</u> \$4.00 <u>3D Printed:</u> PLA 7¢ hardware 20¢

Table 3. Comparison of the cost<sup>1</sup> of purchasing or 3D printing mounting components (commercial images and prices courtesy of GoPro, 3D model images courtesy of Thingiverse)

While the printed parts may not be as strong as the injection molded parts – particularly when shear forces are applied parallel to the build plane – the pricing makes them more than worth a try.

***Aesthetics and customizations.*** Another, and more important, advantage of 3D printing than the cost to produce parts is the opportunity to freely and quickly customize a part. Is the individual a Denver Broncos fan? Then build their switch activation surfaces using materials with colors that reflect that interest (Figure 18). An AT device that showcases its user's interests and identity is likely to be more highly valued by its user and less likely to lead to stigmatization by others.

<sup>1</sup> The cost of the 3D printed part was based on an average cost of \$0.025 per gram of PLA plastic and the number of grams of material per object as calculated by the Cura open source tool path software.



Figure 18. Switch activation surfaces in Denver Broncos colors

Once a part has been 3D modeled it is a simple matter to modify the model and reprint the part. No new tools or molds need to be constructed which can lead to significant costs and delays. Changing the design by 1/3 of an inch is no different from changing it by 3 inches, so there is no need on the part of a user to be reluctant to ask for a change to make the device work better – or even to experiment with a change that just “might” make the device work better.

***Creative design.*** The Maker community is replete with creative individuals. The Adjustable Angle Switch in Table 1 can position the activation surface of its switch anywhere between 32 and 90 degrees in a single plane. The flexible mounting design shown in Figure 19 is based on the GoPro mounting standard and can position the activation surface of a mounted switch with almost any orientation in 3D space (along with displaying the endearing Denver Broncos colors). The mounting system includes a critical component (in blue) that is not known to be available commercially but was freely available from the Thingiverse website.



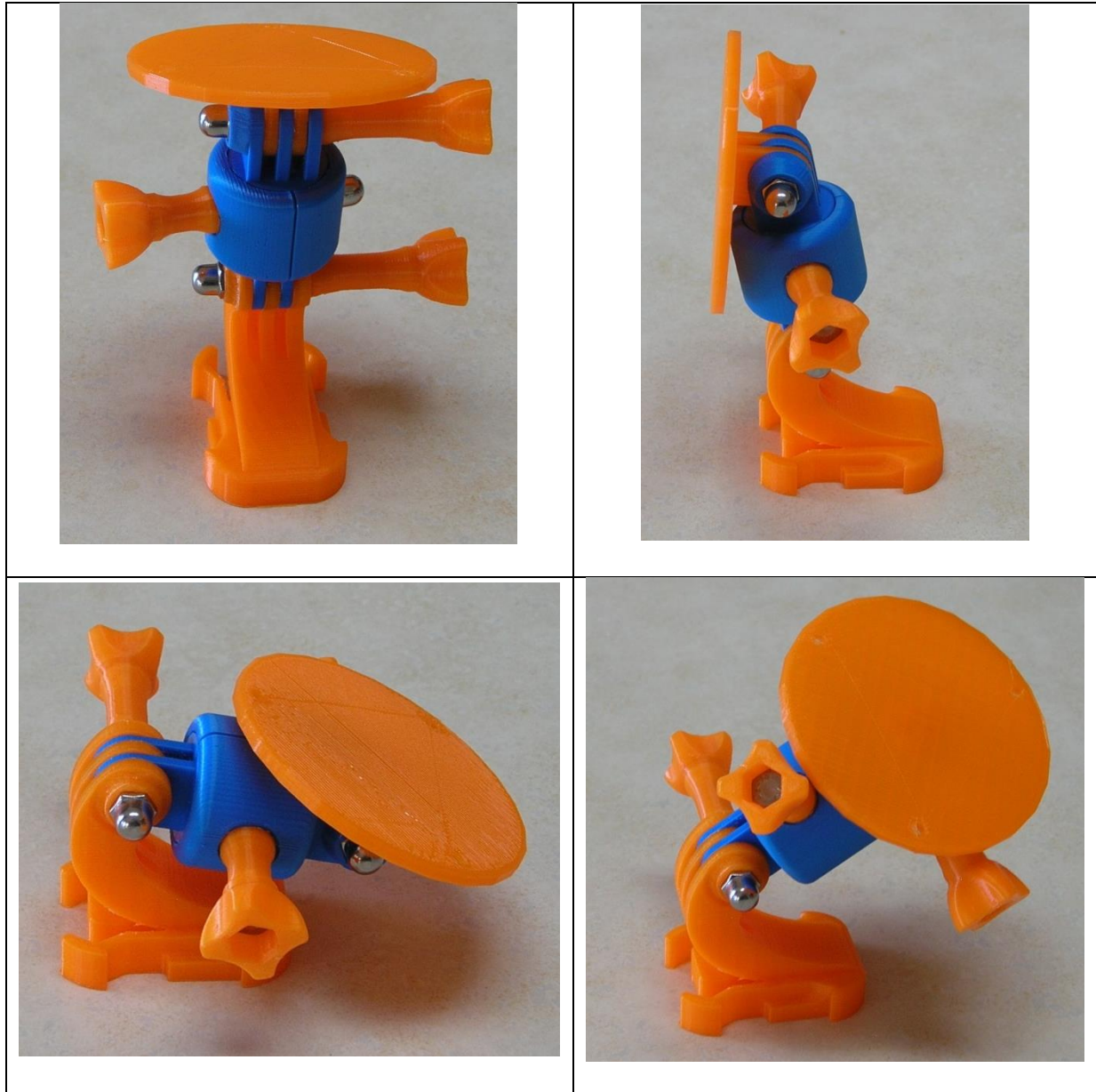


Figure 19. Flexible activation surface mounting angle using custom GoPro-style mount

Finally, what is to stop a creative and capable Maker with a 3D scanner from turning concepts like the images in Figure 20 into one-off, personalized SGDs – complete with speakers within the figure’s heads? Nothing but the will to make it happen. Note that the figure on the right is already available as a 3D model licensed under the Creative Commons.



Figure 20. Figures that could be used as the genesis of custom SGD's

**“There’s an app for that!”** The proposed modular architecture for simple SGD's breaks out the switches and speaker from the typical monolithic system. That leaves only the message server module for the storage and retrieval of voice messages. Commercial smartphones and tablets are quite capable of making voice recordings and playing back those recordings via a wired or wireless speaker. Both the iOS (Apple) and Android operating systems support the use of Bluetooth switches for accessibility. One can find many apps on iTunes and Google Play that allow smartphones and tablets to be used as low cost AAC devices. Two of those apps in particular, Proloquo2Go and GoTalk Now are mature products with a rich history. Both products support switch access and both support speech synthesis in multiple languages including regional, age, and gender variants. An individual with a disability would be able to choose a voice that matches their own region, age, gender – or just mix it up based on how they are feeling at the time.

The smartphone or tablet could be packed away safely within 100 meters of the switches being used for communication (the supported range for class 1 Bluetooth devices) or mounted on



the individual's wheelchair. Conversely, the smartphone or tablet could be mounted directly in front of the switches and used a scaffold to indicate the intent of a switch through the display of images or symbols. iPhone and iPad mounting models with GoPro attachment features are readily available on the Thingiverse site.

Many other communication apps are available for Apple and Android mobile devices. It is possible that one or more of these may provide the minimal functionality needed to act as the message server in an SGD system. It is also possible that one of the many individuals in the Maker Community who focus on mobile app development could be inspired to create just such an app.

### **Conclusion**

Two modular and closely related architectures for assistive technology devices are proposed in this paper – the first in the domain of control (i.e., switches) and the second in the domain of communication (in this case, simple speech generating devices). The primary drivers for these architectures are: design for variation/customization, design for innovation, and design for maintainability...goals that are difficult to achieve with monolithic architectures. As stated in each of the Design for X sections, a modular architecture, particularly one that emphasizes low coupling and high cohesion, can more easily be customized (DFV), maintained (DFM), and innovated upon over its life cycle (DFLC).

Customizability is achieved by defining modules that are simple and interchangeable. The simplicity means that the people closest to the individuals with disabilities can maintain a manageable supply of varied components at relatively little cost. Creating a custom solution is as simple as determining the need, desires, and abilities of a client and then creating the solution in

real-time by plugging, snapping, and screwing together a collection of parts – each with focused, specific functionality.

The goal of maintainability is grounded in the same concepts as customizability. The architecture is designed to be as easy to disassemble as it is to assemble. Parts are inexpensive and troubleshooting a problem is as simple as swapping out one or two parts in sequence until the device begins to function properly again. All repair is simple enough for the user or a caregiver to perform and parts are inexpensive enough to maintain a small inventory as backup or they can be scavenged from other devices. Fundamental modules of the architecture like the switch core are designed to do a simple, focused task with high reliability across the portfolio. Modules like the message server have more complex functionality to perform but, as shown, can easily be replaced by common consumer products like smartphones and tablets. The entire simple SGD product domain can reasonably be decomposed out of existence with the result being a more functional and empowering device.

The goal of innovation is met by allowing the modules to be modified and improved upon with little consequence for the other modules of the system. Focusing on a single module allows the designer to ask the question, “Is there another, better, faster, cheaper, and/or more aesthetically pleasing way to achieve the same end?” When the answer is one that pushes the product closer to the user, as with flexible configuration and customization, and further from the manufacturer, the result is likely to be one where devices become a closer fit to the individual rather than the converse.

Unfortunately, because the market for AT devices is small and highly varied in its needs, this has led to the existence of small, conservative manufacturers who produce monolithic products and are not in a position financially or psychologically to rearchitect their designs or

manufacturing processes. The end result is a selection of devices that are small in number, stagnant in their design, and isolated from the benefits and sense of community inherent in the technologies available to the general public. The situation is unlikely to change as long as mass production goals and methods form the basis of the manufacturing processes of these companies. This is where rapid manufacturing, like 3D printing, can revolutionize the production of AT devices. Because rapid manufacturing techniques are based on general-purpose, computer numerical control (CNC) machines, highly-customized, one-off products, and iterative manufacturing are possible at a reasonable cost. At the same time, these techniques, tools, and modular architectures are simple enough to put into the hands of professionals who work with individuals with disabilities on a regular basis. It need no longer be the case that individuals with disabilities have to “live with” the device they are given. Instead, they can be directly involved in the design and fit of devices that will become a natural extension of their abilities and a compelling indicator of their personality and interests.

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## Appendix A

## Switch and Simple SGD Properties and Values

Table A1. Switch properties and the common values of those properties

Property	Values	Description
Switch Type	<ul style="list-style-type: none"> <li>• Mechanical</li> <li>• Electronic</li> </ul>	The switch is either activated by moving the switch activation surface or by simply being near or in contact with the surface
Connection Type	<ul style="list-style-type: none"> <li>• Wired</li> <li>• Wireless</li> </ul>	The switch communicates with the affected system with or without a physical wire
Wireless Connection Method	<ul style="list-style-type: none"> <li>• IR (infrared)</li> <li>• RF (radio frequency)</li> <li>• Bluetooth</li> <li>• AbleNet Wireless</li> </ul>	The transmission protocol used by a wireless switch to communicate with a remote receiver
Activation Type	<ul style="list-style-type: none"> <li>• Lever (Leaf, Ribbon)</li> <li>• Pneumatic (Sip/Puff)</li> <li>• Pressure</li> <li>• Proximity Sensor</li> <li>• String Pull</li> <li>• Joystick</li> </ul>	The direction of motion and type of force by which the switch is activated
Activation Surface Type	<ul style="list-style-type: none"> <li>• Smooth Plastic</li> <li>• Cloth Over Smooth Foam (i.e., Pillow Switch)</li> </ul>	The component of the switch with which the user directly interacts
Activation Surface Color	<ul style="list-style-type: none"> <li>• Red</li> <li>• Blue</li> <li>• Yellow</li> <li>• Green</li> <li>• Beige</li> </ul>	The majority color of the activation surface, the activation surface color may differ from the color associated with the remainder of the switch in order to provide a visual target for the user
Activation Surface Shape	<ul style="list-style-type: none"> <li>• Round</li> <li>• Square</li> <li>• Rectangular</li> <li>• Spherical</li> <li>• Cylindrical</li> <li>• Wand</li> </ul>	The 2-dimensional or 3 dimensional nature of the activation surface selected to match the control site of the user, square and rectangular shapes can be packed more tightly in grid configurations
Activation Surface Contour	<ul style="list-style-type: none"> <li>• Flat</li> <li>• Mild Convex</li> <li>• Strong Convex</li> <li>• Second-Order Convex</li> </ul>	The topological shape of the surface with which the user makes contact or approaches when activating the switch
Activation Surface Size	<ul style="list-style-type: none"> <li>• Large (more than 9 cm)</li> </ul>	The diameter or greater dimension of the activation surface that

Property	Values	Description
	<ul style="list-style-type: none"> <li>• Medium (6 cm to 9 cm)</li> <li>• Small (2 cm to 6cm)</li> <li>• Mini (Less Than 2 cm)</li> </ul>	determines the degree of accuracy that they user must demonstrate
Activation Surface Cover Options	<ul style="list-style-type: none"> <li>• Clear Snap Cap</li> <li>• Interchangeable Colored Tops</li> <li>• Interchangeable Overlays (For Grid Style Multi-Switch Configurations)</li> <li>• Cloth/Foam</li> </ul>	The component used to cover the activation surface to contain a graphic symbol representing the intent of the switch or to provide alternative tactile properties
Activation Surface Presentation Angle	<ul style="list-style-type: none"> <li>• 0 Degrees</li> <li>• 30 Degrees</li> <li>• 45 Degrees</li> <li>• Adjustable</li> </ul>	The difference between the angle of the activation surface and the angle of the switch mounting surface, chosen the match the motor capabilities of the user
Activation Force	<ul style="list-style-type: none"> <li>• N/A (For Proximity Switches Or Eye Gaze)</li> <li>• 43 g</li> <li>• 46-107 g</li> <li>• 110 g</li> <li>• 100 g</li> <li>• 132 g</li> <li>• 180 g</li> <li>• 198 g</li> <li>• Joystick: 120 g; Push: 200 g</li> </ul>	The amount of pressure that must be applied to the activation surface in order to close the switched circuit (for a normally open switch)
Activation Distance	<ul style="list-style-type: none"> <li>• N/A (“Range” For Proximity/Near Switches)</li> <li>• 0.015-In/0.0381-Cm</li> <li>• 0.025-In/0.0635-Cm</li> <li>• 0.035-In/0.09-Cm</li> <li>• 0.5-In/1.3-Cm</li> <li>• 1.5-In / 3.8-Cm</li> <li>• 10-Degrees Deflection (From Vertical/Horizontal)</li> <li>• Joystick: 0.5-Oz/1.3-G; Push: 0.1-Oz/0.2-G</li> <li>• Adjustable</li> </ul>	The travel distance of the activation surface from the resting position to the point where the switch closes its internal circuit(s)
Activation Feedback	<ul style="list-style-type: none"> <li>• Auditory (Click, Beep)</li> <li>• Tactile</li> <li>• Visual</li> </ul>	Sensory feedback provided by the switch to indicate a successful closure of its internal circuit(s)
Plug Size	<ul style="list-style-type: none"> <li>• N/A (For Wireless Transmitter)</li> <li>• 9-Pin D Female</li> <li>• 1/8-In/3.5-Mm Stereo Plug</li> </ul>	For wired switches, the configuration of the distal end of the wire

Property	Values	Description
	<ul style="list-style-type: none"> <li>• 1/8-In/3.5-Mm Mono Plug</li> </ul>	
Mounting Plate	<ul style="list-style-type: none"> <li>• Mounting Included With Product,</li> <li>• No Plate</li> <li>• Grasp &amp; Mini Joystick Mounting Plate</li> <li>• Micro Light Mounting Plate</li> <li>• Mini Cup &amp; Trigger Mounting Plate</li> <li>• Pneumatic Mounting Plate</li> <li>• Ribbon Switch Mounting Plate</li> <li>• Universal Mounting Plate</li> <li>• Universal Swivel Mounting Plate</li> <li>• Internal Magnet, Universal Mounting Plate</li> <li>• Wobble Switch Mounting Plate</li> <li>• Gooseneck Mount Included; Eyeglass Mount Available</li> <li>• Safety Pin</li> <li>• Velcro Button/Strap</li> </ul>	Normally provided with the Purchase of the switch or as an optional purchase this is the manufacturer recommended mounting system for the switch
Switch Input Ports	<ul style="list-style-type: none"> <li>• 1</li> <li>• 2</li> </ul>	For wireless switches, these ports (typically 3.5 mm monaural jacks) to allow the user to use an alternative wired switch to control the affected system and treat this switch as a simple wireless transmitter
Compatibility	<ul style="list-style-type: none"> <li>• Android</li> <li>• Google Chrome</li> <li>• iOS</li> <li>• OS X</li> <li>• Windows</li> </ul>	If the switch has accompanying software or a predetermined function and appropriate physical connector, the manufacturer guarantees that the switch will work as designed on affected systems running this operating system
Battery Type	<ul style="list-style-type: none"> <li>• No</li> <li>• Replaceable/Internal</li> <li>• Rechargeable Ni/MH</li> <li>• 9-Volt</li> </ul>	The type of battery required by the switch in order to perform powered functions like wireless communication and special activation feedback
Switch Base Configuration/Frames	<ul style="list-style-type: none"> <li>• N/A (Standalone Switch)</li> <li>• Interlocking (Side By Side)</li> </ul>	For switches that are already or can be combined into multi-switch

Property	Values	Description
	(Top And Bottom - To Create 2d-Shapes) <ul style="list-style-type: none"> <li>• Angle Of Interlock (0 Degrees, X Degrees To Create Semicircular Configurations)</li> <li>• Integrated Ridge To Prevent Inadvertent Switch Activation</li> <li>• Grid (One Or Two Dimensional)</li> </ul>	configurations, this is a description of how the switches are/can be organized and any special characteristics of the inter-switch topology
Inter-switch Properties	<ul style="list-style-type: none"> <li>• N/A (Standalone Switch)</li> <li>• Distance</li> <li>• Angle</li> <li>• Ridge</li> </ul>	The topology of a multi-switch arrangement
Base Interlock Type	<ul style="list-style-type: none"> <li>• N/A (For Standalone Switch)</li> <li>• Rigid</li> <li>• Physical</li> <li>• Magnetic</li> </ul>	For linkable switches, this is the mechanism for affecting a linkage
Support for Reference Image/Object	<ul style="list-style-type: none"> <li>• Platform</li> <li>• 2 Dimensional</li> <li>• 3 Dimensional</li> </ul>	The switch face or switch base includes a mechanism for associating a 2 dimensional image or 3 dimensional object with the switch that provides the user with a hint as to the purpose of activating the switch
Total Weight	<ul style="list-style-type: none"> <li>• Light: Less Than 50 g</li> <li>• Medium: 50 g To 100 g</li> <li>• Heavy: 100 g To 300 g</li> <li>• X-Heavy: Greater Than 300 g</li> </ul>	The weight of the switch including the wire for wired switches and the batteries for powered switches – does not include weight of the mounting system, heavier mechanical switches require rigid mounting systems

Table A2. Simple SGD properties and the common values of those properties

Property	Values	Description
- All switch properties and values -		
Switch Count	<ul style="list-style-type: none"> <li>• 1</li> <li>• 2</li> <li>• 3</li> <li>• 4</li> <li>• grid</li> </ul>	The number of switches bundled with the device
Levels	<ul style="list-style-type: none"> <li>• 1</li> <li>• 2</li> </ul>	The number of message storage locations per switch. Locations are normally selected by

Property	Values	Description
	<ul style="list-style-type: none"> <li>• 3</li> <li>• 4</li> </ul>	positioning a small slider switch on the SGD housing. In a simple messaging device one message can be recorded per location so the total number of messages supported is the product of the switch count and the levels.
Messages per Level	<ul style="list-style-type: none"> <li>• 1</li> <li>• multiple sequential (a “step by step” switch the number of messages is limited by total recording time)</li> </ul>	For simple SGDs the device plays the same, single message for each press of the switch. For step by step switches the device will play the next message in sequence for each press of the switch (may include ability to skip messages by quickly pressing the switch again).
Total Recording Time	<ul style="list-style-type: none"> <li>• 2 minutes</li> <li>• 4 minutes (sequential messages)</li> <li>• 10 seconds (single message)</li> </ul>	The total amount of recorded speech (in minutes) that can be stored on the device. May be specified on a per message basis in which case the total recording time is the product of the time per message and the number of messages.
Switch Inputs	<ul style="list-style-type: none"> <li>• 0</li> <li>• 1</li> <li>• 2</li> <li>• 3</li> <li>• 4</li> </ul>	If supported there is one port per built-in switch. This feature acknowledges the fact that the type or arrangement of switches on the device may not match the needs of the user. This allows the devices recording and playback to be driven by a separate set of switches.
Toy/Appliance Outputs	<ul style="list-style-type: none"> <li>• 0</li> <li>• 1</li> <li>• 2</li> <li>• 3</li> <li>• 4</li> </ul>	If supported there is one port per built-in switch. This feature allows for the device to activate an external toy or appliance when the built-in switch on the device is activated. The intention is to provide positive feedback for pressing the switch.
Speech Recording Components	<ul style="list-style-type: none"> <li>• internal microphone</li> <li>• external microphone jack</li> </ul>	The presence or absence of an onboard microphone for recording messages.
Speech Playback Components	<ul style="list-style-type: none"> <li>• On-Off Switch</li> <li>• Volume control / two volume levels (normal conversation, whisper)</li> <li>• internal speaker</li> <li>• external speaker jack</li> </ul>	A set of components, connected in series that support playback for the stored messages. The message may playback through an internal speaker or an external speaker may be plugged into a monaural 1/8 inch jack mounted on the housing of the device. Volume can be controlled by a variable level rheostat-style component or a two position slider switch.
Mounting/Wearing Options	<ul style="list-style-type: none"> <li>• wheel chair</li> <li>• desktop</li> </ul>	The device may be placed on the lap tray of a wheel chair or another horizontal surface like

Property	Values	Description
	<ul style="list-style-type: none"><li>• hip/belly pack</li><li>• shoulder strap</li><li>• wrist strap</li><li>• wall mount</li><li>• other special</li></ul>	a desktop or mounted on a vertical surface like the wall. The device may be designed to fit in a hip or belly pack (usually provided by the manufacturer), carried via a shoulder strap, or worn on the wrist.