AN ABSTRACT OF THE THESIS OF

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Title: <u>Mechanical Design Under Changing Customer Requirements Case Study: BugID</u>

Abstract approved: ______________________________________

Robert K. Paasch

Customer requirements and engineering specifications will influence the direction of the design in any product, so it is crucial to make the requirements as stable as possible so quality designs can be produced on time within a budget. It would be optimal for requirements and specifications to remain constant but many requirements will change during the evolution of a design. These requirement changes can result in the disruption of the product development schedule, increased development costs, and failure to meet customer requirements.

For this work product development strategies for minimizing the adverse impact of changing design requirements were adapted from previous work in mechanical design, software design and project management. They were applied in the context of new product development for the BugID project, an interdisciplinary system designed to identify arthropods through microscope imaging. In the application four main strategic categories were identified: Customer Interface, Iterative Design Process, Future Analysis and Change Tolerance Architecture. These four categories formed two sets of coupled

categories: a set including customer interface and iterative design process and the set of future analysis and change tolerance architecture. These strategies for design during changing requirements will continually be applied to the development of mechanical design solutions for the BugID project as well as establish a more systematic design methodology for designing under changing requirements. This methodology is anticipated to be applicable to many interdisciplinary product innovation scenarios.

Mechanical Design Under Changing Customer Requirements Case Study: BugID

by
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Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Chris R. Fagan, Author

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1.0 INTRODUCTION

A design problem is solved by satisfying needs that are specified from customers. These needs are qualitative and quantitative, vary in importance and are not static. In order to manage the needs effectively designers use a set of technical activities that support the product development processes called the design process [1]. To complicate the process, the design engineers, project size, project complexity and changes in technology can all influence the product development process. As products increase in complexity and the market generates more competition there is a need to develop and adjust the design process to make it more efficient. These variables commonly result in design engineers being challenged by inadequately defined or changing customer requirements. Unfortunately, in the present design process literature, accommodations for the mechanical design process under changing requirements is not readily available.

This work explores product development strategies for minimizing the adverse impact of changing design requirements in the context of new product development for the BugID project. The BugID project is an interdisciplinary system designed to identify arthropods. The design team researched effective strategies to design when requirements are not fully defined initially or evolve during the design process. Strategies were identified from mechanical design, software design and project management, then were looked at concurrently and adapted for application to the interdisciplinary design process with changing requirements [2] [3]. The following sections will review design under changing requirement strategies, describe the BugID project, and present the application of the combined set of strategies implemented in the BugID project and the results.

1.1 The Design Process

Although the design process is influenced by a set of factors, which may include the engineers, project size and complexity, the components of the modern product development process can be divided into three phases as shown in Figure 1 [1] [4] [5]:

- Understanding the Opportunity
- Developing a Concept
- Implementing the Concept

During the initial phase, Understanding the Opportunity, customer needs are amassed for problem definition. These needs are gathered in a variety of ways including interviews, questionnaires, focus groups and

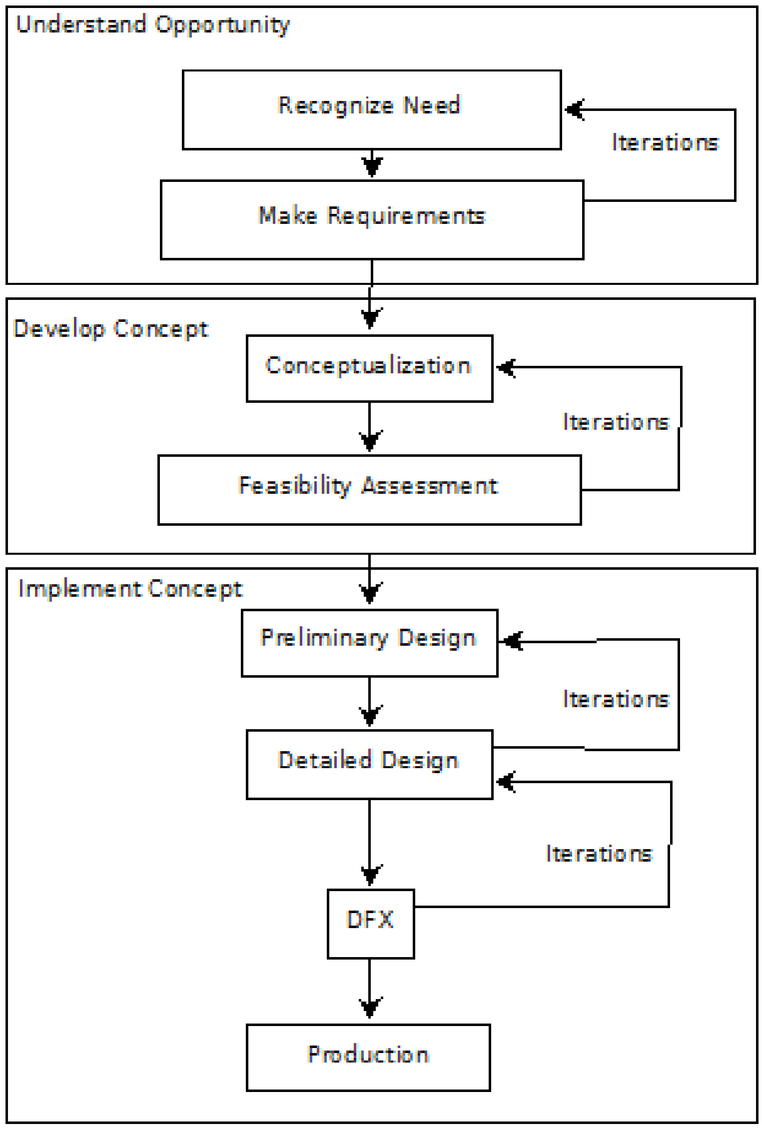

Figure 1: Three phases of the design process.

designers acting as the customer [1]. Statements are then analyzed to define design requirements and are used to develop the actual product design [1]. It is estimated that poor product definition plays a role in 8% of all time-to-market delays. In addition, approximately 35% of product development delays are a direct result of changes to these definitions throughout the design process [4]. Thus, it is important to develop a set of clear design requirements to focus the establishment of product specifications during the design process [6]. For a successful design process the designer must understand the technical design problem and define quantitative needs, in addition to understanding how the design fits within the context of customer qualitative needs.

In the next phase, Developing a Concept, the design requirements are used to develop a product concept. Establishing a concept may be arduous due to requirements being unspecified or never explicitly stated. Some requirements may initially also be considered relatively unimportant or assumed intuitive. Frequently, the technical aspects of a product are not understood by the customer resulting in their need being defined as a qualitative requirement rather than a quantitative requirement. The responsibility to consider all of the requirements for the design concept, even if they are unstated or perceived as unimportant, is consequently governed by the designer [7]. Customers may also be incognizant of what they want so requirements may be underspecified. In this instance, customers must initially make educated guesses as to what their needs could be. If a design is still not sufficiently specified the designer may be required to make estimations about engineering requirements. With requirements then provided or deduced from the client and designer the designer must ensure that the product concept that will satisfy the design requirements is feasible.

Once a feasible design concept has been shown to satisfy the design requirements the final phase of the design process is Implement the Concept. Implementation often consists of multiple steps that increase in the level of design detail as they progress. In most cases this will also necessitate design iterations to account for manufacturing cost and product life-cycle requirements.

The entire design process emanates from customer needs and the requirements that are produced from those needs. A successful designer can interpret the customers' actual needs and extract requirements that are not customer specified. Needs and requirements can be acquired with observation of design trends and making predictions or creating unspecified customer needs. Both approaches can be successful if the customers are well understood and there is sufficient communication [7]. As more knowledge is gained during the product development cycle the requirements may continue to be refined and properly specified. Requirements are also created for interfaces between components or functions and are used to check consistency, track change propagation, and add a measure of completeness. These are often implicit assumptions, but they should be explicitly stated to clearly show the potential effects of change to the overall system [8]. It may be beneficial to categorize the list of requirements into component groups and break down requirements into structured sets of requirements for each component. By establishing sets of requirements the analysis of requirement specifications is eased and confidence in specifications is increased by identifying inconsistencies, but this process can not guarantee completeness and correctness of the existing requirements [8].

1.2 Why do Requirements Change

Even after design specifications are clarified design requirements may change and drastically impact the design of the product [7]. Even if the customer initially conveys their needs accurately, requirements can change as a result of cost considerations, advancements in technology, changing customer opinion or evolving product development.

Evolving product development often arises in the development of new products where a series of prototypes are used in order to learn the nature of a product through several generations. During this process initial requirements are tested in the first generation, modified, and then a new set of requirements are identified for the second generation, with the cycle continuing until design requirements are satisfied. Existing products may also need to be revised in this manner to meet the needs of new customers or market desires.

Two categories can be used to summarize the factors that result in changing design requirements:

1. A change in the target value for the requirement.
2. The addition of a requirement.

A change in target value is when a requirement has been previously defined but the value of the requirement changes, such as, how bright a light should be. These are by definition mostly quantitative and commonly result from needs that are identified but not well understood or well communicated.

In the second case, addition of a requirement, a completely new requirement that was not initially included in the design requirements is added. These new requirements can be either qualitative or quantitative and usually arise from initially undefined or latent customer needs.

Design requirements are often interdependent and the satisfaction of a requirement may depend on the satisfaction of another requirement. Requirement changes during the design process are usually costly considering the implications are often uncertain. Correlative to both time and money, changes that will affect several parts of the design are increasingly dramatic [7]. Requirement changes due to poor pre-design or re-work can accrue more cost due to the additional resources needed to correctly complete the design phase [4].

Regardless of the additional cost of change to design requirements, some change should be anticipated during the product design process, and, in some instances, may be an unforeseen benefit. Changes may be advantageous if they result in an improved product [9] and can potentially represent significant opportunities affording a competitive advantage [8]. However, having a design strategy that actively attempts to minimize the negative impact of changes to a developing design needs to take precedence over potential benefits.

Increasing complexity of design problems and the subsequent specialization needed to manage technological advances has led to the formation of teams consisting of varying disciplines to collaborate throughout the design process. However, when technical and business specialties merge in an effort to increase product quality and decrease product development process time, a challenging design process emerged within the collaborative product development project [10] [11] [12]. The collaboration compounds the opportunity for customer needs, cost considerations, technological changes and results in changing design requirements.

2.0 STRATEGIES FOR DESIGN UNDER CHANGING REQUIREMENTS

Changes to design requirements can occur throughout the design process as well as during redesign. Most product development models include the steady evolution of the initial design, which serves often to eliminate mistakes and to accommodate for new requirements [13]. Design changes are a constituent of the design process but often the changes are expensive and time consuming to implement. In an effort to counter the additional costs, a number of approaches have been developed to assess the impact of a design change [14]. The disciplines of mechanical design, software design and project management all have separate strategies on how to design with considerations for changing requirements. Although these independent strategies deal with changing customer requirements they may not be directly interchangeable between disciplines without modification.

2.1 Mechanical Engineering Approaches

Research in mechanical engineering design on changing requirements has focused on change with a risk assessment tool. Changes to a set of requirements can be costly and difficult to carry out, making their impact assessment a monetarily driven objective. Assessment of this risk can be beneficial to managers responsible for project budget and schedule. Predicting change and change propagation through a product's life span can facilitate engineers with allocating the needed time and resources [15]. The ability of an engineer to track changes can provide valuable experience for designing future products but a drawback is that this approach is often applied in a reactive fashion. Tracking changes only permits the designer to address problems after the changes have come to pass rather than before the required change happens. The benefit to this process is with re-designs or future designs rather than the current design in process.

2.1.1 Designing for Flexibility

An approach to creating a more proactive design process is to design flexibility into systems and plan for changes. With increasing numbers, design engineers are realizing that designs are expected to have longer life-spans in an increasingly complex and dynamically changing environment [16]. Requirement changes are likely to occur in long-lived systems and, by embedding flexibility into a design, design engineers can design for change rather than resisting change or passively accepting it.

Allowing for flexibility means designers can incorporate adaptable product architectures that may accept changing requirements. Product lines and product families that satisfy the core requirements, while allowing other requirements to change, allocates more flexibility in a design. These components are not optimal in design work, and may be called over-designed, but can prove cost effective for future generations of a product. If the current product is designed so a component can absorb a large change in a specification before requiring redesign the possibility that product will be changed decreases [17].

For an optimized design, only requirements that are likely to change should be translated into flexible components. For those requirements that are not likely to change more emphasis should be placed on functionality, since these components are likely to remain throughout the design process. Increasing the design flexibility increases its complexity, which in principle, is undesirable. A designer should not create complexity within a component that can be designed simply; it should be determined what should be designed to allow for flexibility [7]. An assessment should be made whether the benefits of flexibility outweigh the cost to functionality, which will include a evaluation of what requirements are most likely to change as well as the target lifespan of the system.

2.1.3 Design for Variety

The Design For Variety (DFV) method [17] uses product platform architecture to provide a structured approach to reduce the amount of redesign effort for future generations of a product. For large projects a system architecture can be used to break down the design into smaller subsystems at each level of the design hierarchy [7]. The DFV has the advantage of being a simple and inexpensive technique to determine potential design changes and the methodology makes use of standardization and modularization techniques to reduce future design costs and efforts [17] [18]. Two indices develop using the DFV method to measure a product's architecture. The first, called the Generational Variety Index (GVI), is an indicator of the amount of redesign effort required for future iterations of a product. The second is called the Coupling Index (CI), and is used to gage the extent of coupling among the different components in a product. The Design For Variety method can be used to help reduce the impact of variety on the life-cycle costs of a product [17] [18].

2.1.4 Design Freeze

Freezing requirements is another way mechanical designers can accommodate for changing requirements. The main goal of freezing requirements is to reduce the likelihood of design changes. The major benefits from using design freezes is the ability to structure the design process and to control design changes [14]. A design freeze marks the end of a development stage where requirements become fixed before the design can continue [14]. Design freezes have the benefit of pushing any design changes to future product generations, which can be constructive in an iterative design process. However, when the exact product requirements are uncertain or the requirements may change, it is advantageous to postpone a design freeze.

Another concern is that some changes that are due to safety concerns, problem corrections, or altered customer requests, will still have to be carried out regardless of whether a component is frozen. Changes after a freeze are likely to be more costly, and the cost will continue to increase the later the change is implemented [14]. Although freezing the design will stop the requirements in the design from changing it will not help mitigate changing requirements, and has potential to be harmful in an environment where the requirements must change.

2.1.5 Functional Design

The functional design method describes a system and its sub-systems in terms of its functions. The design method concentrates on high-level functions that can be decompressed into low-level functions to find design solutions [1].

As stated previously, requirements can change due to poor understanding or interpretation of the actual customer need for the product. Functional design can reduce some of these changes by linking needs directly to the functional decomposition rather than directly to a concept or form. This allows implicit needs to be draw out by the functions while still allowing the ability to map the outcomes back to the customer needs. The designer is able to focus first on linking the customer needs to a function and then to the form of that system [1].

After identifying the functions in the system the functions can be mapped to show the sub-system interconnects with a functional model. The functional model will allow the design team to easily see what sub-systems are dependent on each other allowing for implementation of concurrent design and modular design. Functional modeling is a clear way for design teams to record and communicate product functions and flows while still providing the needed design freedom early on in the process. This clear communication with freedom allows for critical early solutions to be implemented without freezing designs [4].

2.2 Project Management Approaches

The field of Project Management has developed some approaches to reconcile the impact of design changes with success. Although mainly focused on the management aspects of budgets, personnel structure and scheduling, rather than the design processes, some of these strategies can be translated to mechanical product design.

2.2.1 Dynamic Product Development

Significant research has been conducted in the area of Dynamic Product Development (DPD) to explore management methods that keep design cycles short, while still allowing for design changes [11]. DPD is based on a management plan that provides concept development during each design iteration and encourages a “planetary” organization with sub-project leaders managing small project groups and reporting to the main project leader [11]. In some environments this management approach can postpone concept iterations and make the design process more robust to change by allowing idea generation, analysis and data collection to happen simultaneously.

2.2.2 Scope Creep

The idea of the scope of the project changing during the design process is called Scope Creep. Scope creep is managed as a risk to the project with positive and negative impacts [19]. This viewpoint is similar to some mechanical design and management methodologies and can be translated across disciplines. This project management approach does not specifically answer the question of how to implement a design process that is scope creep friendly, but focuses on the management approaches, which is less beneficial to the designer.

2.2.3 Iterative Product Development

An iterative product development strategy been useful during changing requirements with an emphasis on quickly producing designs that meet certain requirements. Design requirements and product architectures are developed iteratively by simultaneously addressing requirements, specifications and product designs. To be effective, this strategy needs quick turnover of evaluations, designs and prototypes and the evaluation and frequent prototyping can help identify conflicts throughout the design process [20]. The iterative design approach may forgo quality for quickness with the understanding that the current design will be altered and serves the purpose of advancing the design process. Higher quality iterations may be more informative, but a number of rapid iterations can test a broader range of components. Early in the process iteration quality can be substituted for iteration quantity, and as the design becomes more concrete the focus should switch to higher quality iterations.

It may also be beneficial in an iterative approach to freeze some design components from model to model. By changing a single or small number of components at once, it is easier to test and identify the success of those particular components. This practice can be facilitated by identifying those requirements and corresponding components that are more enduring and center design work on those components. Once a quality model foundation has been established, further components can be implemented and tested.

2.3 Software Design Approaches

The field of software design has investigated designing under changing requirements to a greater extent than the mechanical design discipline, thus developing methods that can be adapted to work with the mechanical design process. However, considerations must be made when adapting software design approaches to mechanical design because the software system strictly transmits information, while mechanical systems typically transfer material and/or energy in addition to information.

2.3.1 Flexibility

Software is often the most flexible and readily changed component of a system [15]. Several methods used in software engineering consider changes in evolutionary software development. These methodologies generally only identify the immediate implications of change within the immediate sub-system and are not capable of exploring the results of change that propagate through complex systems with differing mechanical interactions [21]. These models are not appropriate for mechanical design where component interfaces are not as explicit and involve more than information transmission.

When the interfaces and system interactions are well described and well known it is possible to apply a modular or evolutionary design theory to a mechanical system. When the system complexity and component interactions are well identified and designed it is possible to modularize even complex electro-mechanical systems with many interactions [22]. In complex products, components may be highly interconnected and changes to one component will likely affect other components that are not directly connected to the component being modified. With knowledge about past change propagation, design efforts can be directed toward avoiding change to sub-systems that will cause major expenses, while allowing change where it is easier to implement [13]. When designing for flexibility it is important to gain knowledge about the interactions between components in a system, especially when applying these ideas to mechanical system design.

2.3.2 Change Prediction Method

The Change Prediction Method (CPM) tool [21] is a software program being developed for predicting change propagation. CPM is a technique for analyzing indirect changes and calculating the combined risk that a change to one component will have on others. Reliable change propagation information is important for successful change management. The CPM tool makes use of Design Structure Matrices (DSMs) to provide a simple, compact, and visual representation of the probability that a change will propagate from one component to others [21].

2.3.3 Customer Involvement

Customer involvement in the software design process cannot be overstated, and the same can be said when applying this idea to the mechanical design process. This approach seeks to identify the social, technical, economic, and organizational objectives as perceived by the different stakeholders [23]. When designers face obstacles that may hinder a product design or errors in designs they are often the result of miscommunication between customers and designers as well as within the multidisciplinary teams [20]. With this approach, communication problems can be reduced if members of the community and design team are involved with all levels of the analysis, design, evaluation and implementation of the system. Coupling active customer participation with rapid prototyping methods forms the foundation for identifying unanticipated customer requirements expeditiously [7]. To help prevent delays or miscommunication throughout the product development process effective communication between the designers and customers is important [11].

2.3.4 Iterative Design

Similar to the ideas in project management, software design suggests iterative designs and product evolution. Software design suggests a complete list of requirements should be explicitly written for future evaluation and evolution. It is helpful to de-construct requirements into component parts and structure the requirements so they are easy to follow and analyze. It is also important to identify and define inter-requirement rules and relationships between different components [8]. When changes are made to requirements a new revised list must be formulated. These lists are useful for tracking evolutionary changes in the original requirements and will help with prototype evaluation and identifying conflicts throughout the design process.

2.3.5 Future Changes

Future Analysis offers techniques that may aid in early identification of requirements subject to change [23]. Customers or partners in the project may be able to forecast possible requirement changes, but prediction of changes in the design process should also be analyzed continuously throughout the design process and in each of the sub-groups involved in the project. Knowledge of future plans can help place priorities on engineering requirements. Future analysis may involve designing a prototype with plans to redesign based on the assessment of the prototype. Experience, early identification of potential for change, and past history on the project can all be influential in predicting changes [9].

Recognizing which requirements are likely to remain in future iterations will direct the design. Some components will be more inconsistent and should be given more attention. In this analysis it is important to analyze the design and determine which components satisfy which requirements. If the mapping between component and requirement is known then if the design targets are changing or if new requirements are being added it can be seen. This allows the design to be made more robust to the two types of requirements: the ones that may have changing targets, and the requirements that may be added in later due to latent needs. When the enduring requirements are identified, even if they have changing targets, the design direction can focus the majority of attention on the components that are effected by the enduring requirements. Other components that are not related to enduring requirements, and as a result, are likely to transform can be targeted differently than more permanent ones in order to minimize some of the negative affects of these design changes.

3.0 THE BUGID PROJECT

The BugID project is a collaborative research development effort by multidisciplinary teams of entomologists, computer scientists, and mechanical engineers. The goal is to generate an automated mechanism for identifying species of particular insects [3][24]. The BugID project seeks to advance ecological monitoring through automated identification of insects using machine learning and pattern matching techniques [2]. In conjunction with computer algorithms, mechanical manipulation, and high-resolution photographs it is the hope that extensive insect population counts can be economically obtained. Efficient identification information will be advantageous to ecological science and environmental monitoring.

With project customers coming from varied backgrounds the BugID project evolved into an interdisciplinary design environment. This environment was the catalyst for many design changes and provided a need for a design process that was successful under changing requirements.

The mechanical engineering teams' responsibility was to design and build a mechanical system to capture images. The mechanical design requirements for the project centered on capturing quality bug images that the computer science team could use to develop and test their identification algorithms. Hence, the computer science engineers are the primary customers for the mechanical design work.

The other customers include the entomology team and have requirements for device usability and functionality while handling insects preserved in glycol. The long-range consideration of this project is for entomologists and other scientists who will become the customers of the project.

The mechanical design team's approach is an iterative process with the evolution of changing design requirements through several generations. At the very beginning of the project the focus was on stonefly larvae, which is an indicator species for water quality in streams and rivers. These insects range from one centimeter to over five centimeters in length and are most easily identified by the patterns on their backs [2]. As progress was being made creating identification algorithms, by the computer science team, work began on a different group of insects known as soil mesofauna. These tiny organisms live in soils and are sensitive to soil type, chemicals in the soil, and land management procedures making them excellent indicators of soil biodiversity [2]. These two groups of insects differ enough to have unique requirements for image quality and require separate mechanical systems for capturing images. Images of these two groups of insects can be seen in Figure 2.

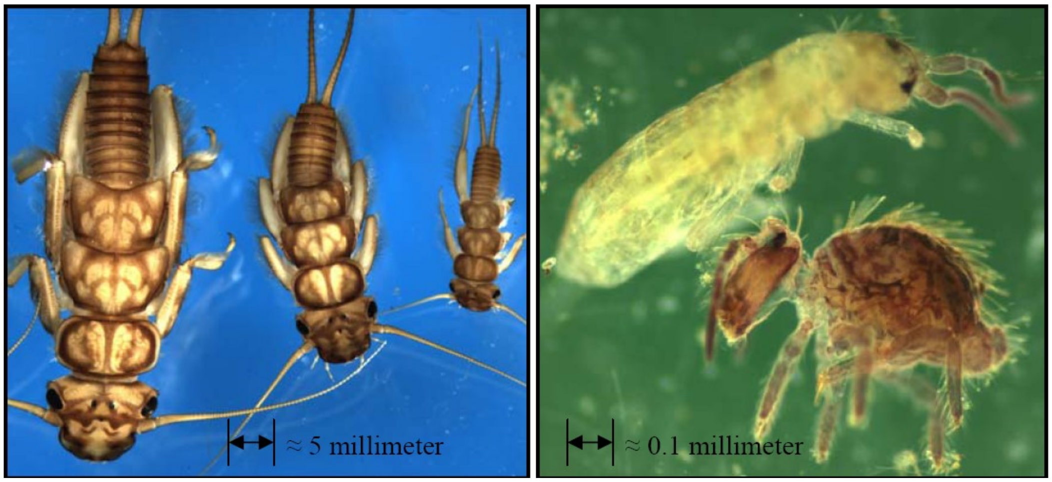

Figure 2: Stonefly larvae on the left and soil mesofauna on the right.

The mechanical design team has developed a working prototype for imaging stonefly larvae and soil mesofauna, shown in Figure 3. The basic designs consist of an insect holding and viewing apparatus, a transport mechanism, and a camera in conjunction with a microscope. For the stonefly larvae a holding and viewing apparatus was placed under the microscope [24]. For the soil mesofauna the holding and viewing apparatus was a petri dish placed atop a horizontal LCD screen. The LCD screen is used to give the images a blue or green background for segmentation and transparency estimation. The screen is mounted on top of two motorized stages for motion in the *x* and *y* directions. The holding and viewing apparatus was then bolted to a platform that held the microscope column above the LCD screen. Images were obtained using a high resolution camera mounted on the microscope. The camera is controlled by a computer and captured images can be viewed in real time. The design requirements also call for a way to remove identified organisms from the petri dish after identification.

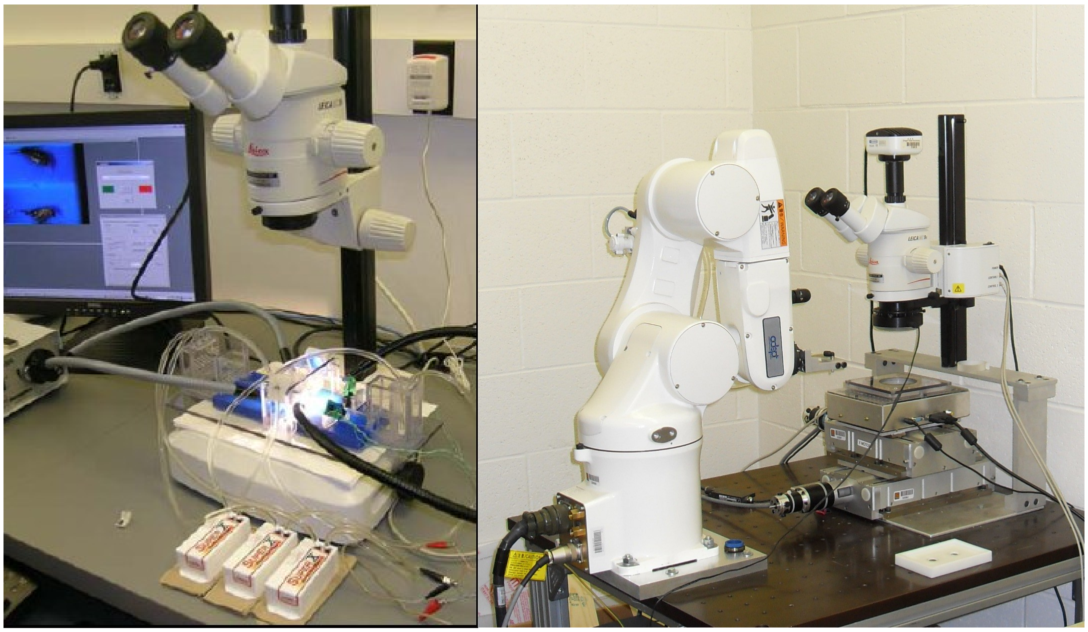

Figure 3: The two imaging systems, stonefly larvae system on the left and soil mesofauna system on the right

The goal of the project is to develop a new product that meets all of the customers' needs, but at this stage, not all the specifications are known [3]. From the beginning of this project, the mechanical design team has been working under a loosely-defined set of customer requirements provided by the computer science and entomology teams who continue to identify what they require for their recognition algorithms. Due to the nature of high-level design uncertainty in developing a new product in an interdisciplinary environment, the design requirements could not be fully defined up front and have been explored through a process of prototyping and testing. This has rendered the product design process highly unpredictable and fraught with changes to both the design requirements and the product design. Throughout the three years of this project there have been multiple product development iterations and the design continues to be improved.

With the working prototypes for identifying stonefly larvae and soil mesofauna, design improvements and overall alterations continue to necessitate changes by the mechanical design team. In order to ensure the quality of the holding and viewing apparatus, and the success of the BugID project as a whole, a strategy needed to be in place that aligns the team with the changing requirements, and minimizes the impact to the existing design.

4.0 DESIGN UNDER CHANGING REQUIREMENTS IN THE BUGID PROJECT

The BugID system is exploring new areas in both arthropod imaging and computer vision. As a result the anticipated performance of each of the subsystems (computer science, mechanical engineering and entomology) may be hard to predict. Each of the subsystems in the project is essentially the customer of the other subsystems, so for each subsystem to excel they want the best performance from each of the other subsystems. However, because each subsystem is pushing the limit simultaneously, no one group is really sure what the “best” is. To avoid anticipating performance that will be unobtainable, the subsystems frequently compromise by meeting “in the middle”. While this can help with performance expectations, it can also create frequently changing requirements due to the continual change driven by compromise.

The mechanical team in the BugID system was focused on designing to mitigate the negative effects of changing customer requirements. The approach used by the mechanical design team occurred in four main categories:

1. Customer Interface
2. Iterative Design Process
3. Future Analysis
4. Designing for an Architecture that Tolerates Change

4.1 Customer Interface

From previous work with design under changing requirements, it is important to have an effective interface with the customers during the entire design process. This interface is responsible for exchanging important information regarding changes to design specifications [7]. To help facilitate the interface between the customers and the design team, it is important to make communication as open and as simple as possible. There must be an understanding of the potential barriers and impediments to communication between involved parties.

The BugID project has seen changes in research assistants, graduate students and principal investors. Also, two members of the computer science team work at universities other than Oregon State University. Each time there is a change, new relationships need to be built in order for communication to continue. Fostering open communication requires strong relationships built on trust between customers and developers. This approach was used extensively in the BugID project among the interdisciplinary team, and was particularly effective in developing requirements and enhancing communication. These requirements are assessed by the entire group based on importance of the requirement and difficulty of completing the requirement . By going through the product assessment process together, the design teams can collaborate to create a suitable understanding of product direction and design requirements.

Requirements were shared throughout the group by way of meetings and documents. When documents and requirements change, they must be tracked and a system ensuring the use of the current version is necessary. One approach implemented was through a *wiki* page. The wiki page allows access and edit ability to all members of the team and the created documents are easy to change, keep current and communicate with. The wiki automatically tracks when the document was changed and who made the changes. By keeping the previous editions it allows all members to modify freely without fear of losing information. Like any communication tool, however, the wiki page needs proper participation and a motivator for the use to be successful.

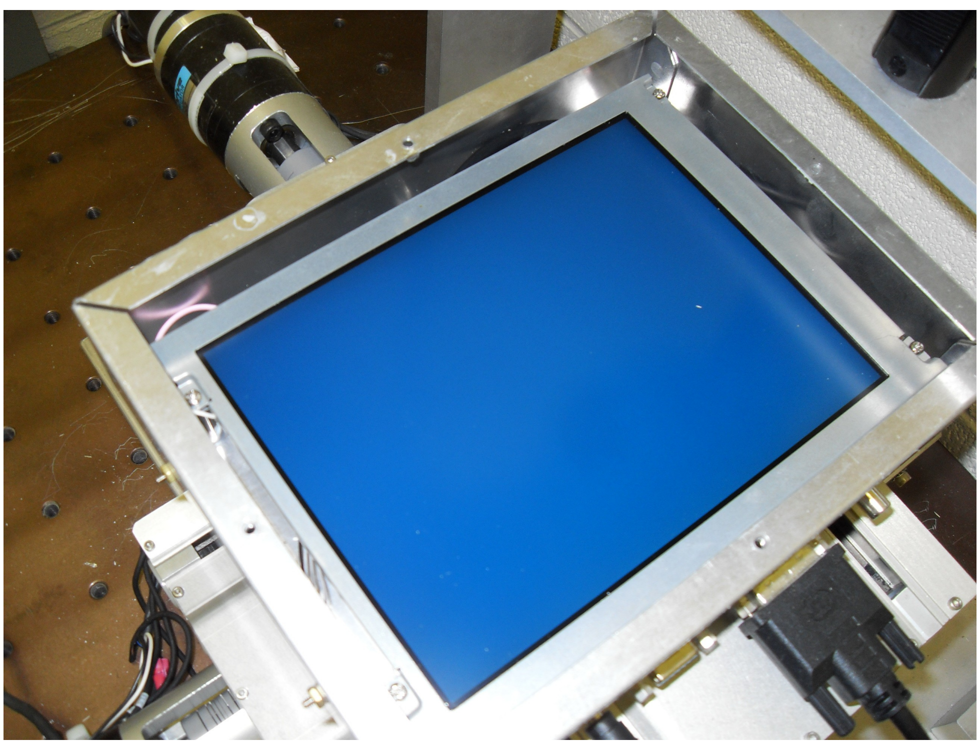

Figure 4: The LCD screen that provides a background for soil mesofauna imaging.

When developing design requirements two pitfalls in the customer interface are over specification and omitted customer requirements. If requirements are over specified they can result in unnecessary functionality and complexity. If the necessity of a requirement is unclear it may be beneficial to test the requirement separately. For example, the BugID project design team tested the effect of different background colors needed for bug segmentation by placing transparent colored plastic sheets under the microscope. It was agreed that the requirement was significant, and was actualized by an LCD screen component seen in Figure 4. This addition of a LCD screen showed a previously omitted customer requirement of being able to control the background from the user software. Although this requirement was established by independently testing requirements, the development process would have been more direct if the full set of requirements between the components had been initially clarified.

4.2 Iterative Design Process

The general design approach in the BugID project was an iterative approach that used prototypes to test and formulate requirements. When the design for the stonefly larvae holding and viewing apparatus was initiated, several iterations of the transport tube were tested. Testing various sizes, shapes, and lengths of tubing, as well as special grooves cut in solid plastic, were part of the iterative process. Mock transport systems were designed, built, and tested several times before a design was selected and incorporated into the holding and viewing apparatus. Other iterations were made to alter the viewing angle and direction. Several iterations of the transport apparatus are shown in Figure 5.

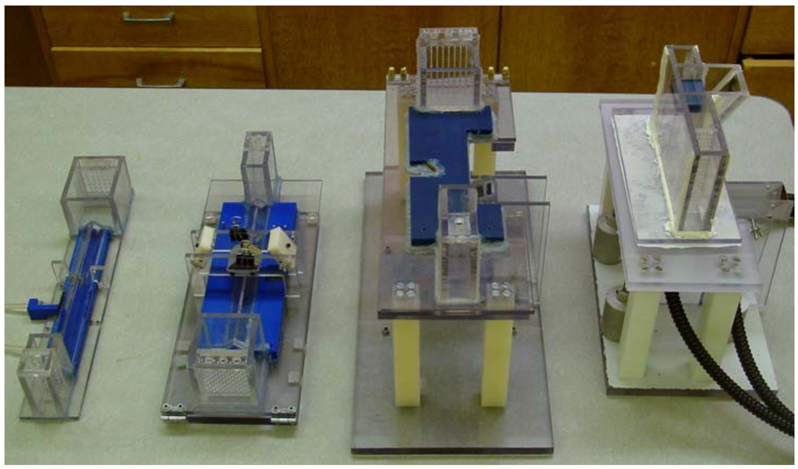

Figure 5: Several iterations of the stonefly larvae transport system.

On the soil mesofauna apparatus, in the design iteration of the ring lighting attached to the stage, the second prototype provided more light and added the ability to adjust brightness. These additions added complexity to the design but the combination of design iterations and building in flexibility allowed the requirements of the LED lighting to be determined and finalized.

4.3 Future Analysis

The idea of foreseeing future changes can be applied to mechanical design and a robust design is one that can cope with alternative futures [23]. Building flexibility into a system can be beneficial but costly so it is important to determine the optimum places in the system to build in flexibility [23] after attempting to consider likely alternative futures.

The base platform, seen in Figure 6,of the BugID system was designed to be robust and flexible to accommodate future components. The base platform for the soil mesofauna holds the viewing apparatus, and is where the microscope, lighting and x-y stages are mounted. Through future analysis it was determined that the stage translation, background color, bug extraction and lighting all had potential for change and the base platform should be able to accommodate such changes. The base has not been altered in several apparatus iterations.

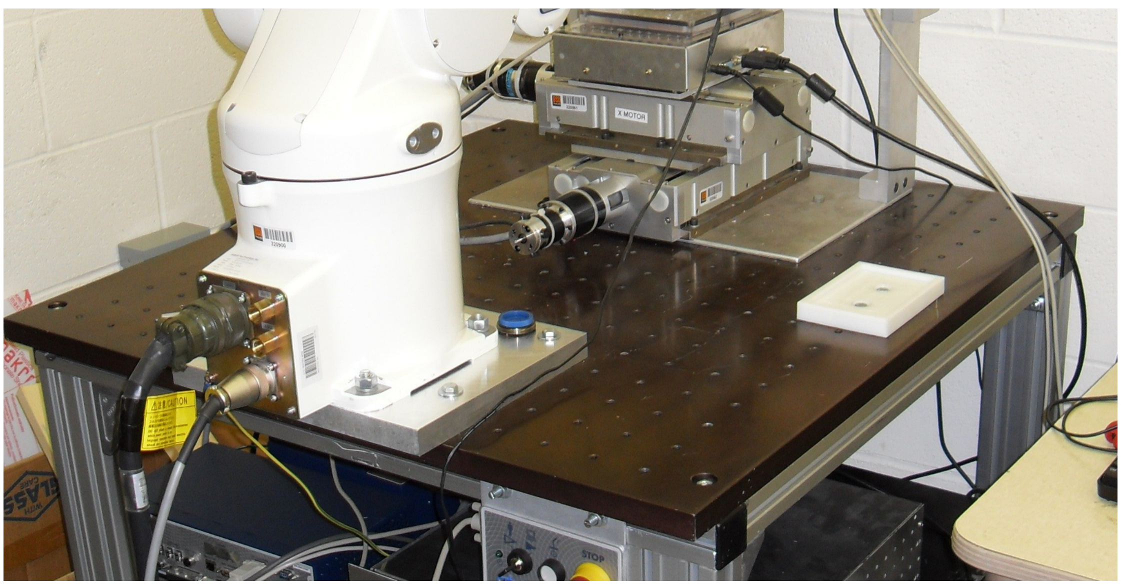

Figure 6: The platform for soil bug imaging system.

It was known early in the BugID process that a blue background would be fundamental in capturing quality stone fly images, but the value and intensity of the blue was unknown. It was determined that the background could vary greatly and it should be robust to these changes. An LCD screen was chosen for the initial prototype due to its versatility for rapid color value, intensity changes and the ability to easily experiment with all parameters.

Another component in the project is a robotic arm, seen in Figure 7, that extracts the mesofauna from the petri dish once it has been identified. It was identified early on there was limited knowledge about the most efficient way to

Figure 7: Six axis robotic arm for soil mesofauna manipulation.

extract the mesofauna. The mechanical engineering group determined the extraction would need to be robust to many linear and angular translations including velocity, acceleration, position, force and orientation. A six axis industrial robotic arm was chosen because of it ability to quickly cope with these changes. This was an over compensation that allowed flexibility and the ability to tolerate developing requirements. This was aided by interchangeable end effectors.

One component that could not change was the petri dish. From lighting, extraction, imaging research and testing it was decided that a size or shape change in the petri dish could effect factors of the systems that could not easily be changed such as: lighting intensity, lighting shade, light coverage, extraction accessibility and bug shape or size. The decision was made to use a standard size and shape of the petri dish that was easily obtainable.

4.4 Select Architecture that Tolerates Change

From future analysis for the BugID project some systems were determined to be likely to change in the future. These are systems that frequently changed in the past and/or had requirements that were known to be difficult to satisfy. In these systems it was helpful when a system architecture could be chosen that is tolerant to change.

A LCD screen was chosen to be the image background due to the ability to accommodate changes. Employing the LCD allows changes in shade, intensity and color. Also, because it is connected to a computer the screen has the potential to tolerate additional changes, such as using images, gradients, patterns, etc..

The light ring, seen in Figure 8, for the soil mesofauna holding and viewing apparatus was built with change tolerance in mind. For the design iterations the power supply for each design was the same and the product architecture for the electrical connection allowed for testing each design without changing the holding and viewing apparatus. This tolerance to change made it easier to iterate the device.

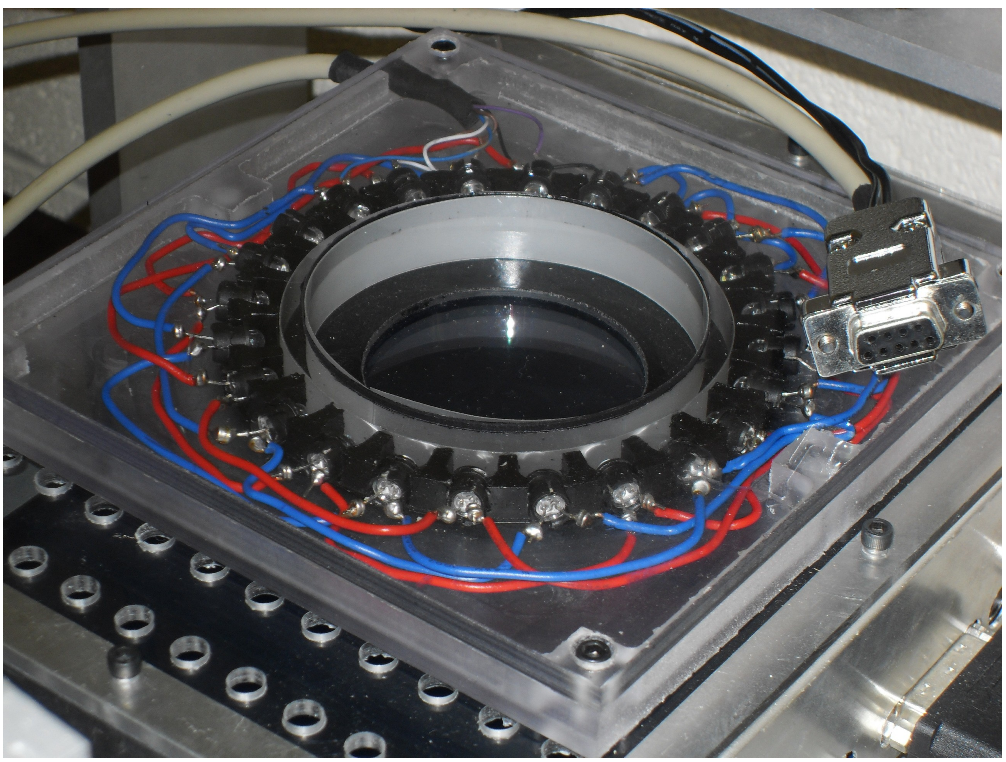

Figure 8: The LED light ring and connector used for the soil mesofauna imaging system.

However, in the light ring there were places for improvement. It would have been beneficial to use a flexible LED architecture that allowed for changes in the number and type of LED. This may have eliminated the need for one of the design iterations. Instead, separate designs were made and LEDs were soldered together at pre-drilled holes in the housing, also in Figure 8. Flexible product architectures may be difficult to utilize, but in projects with changing requirement the benefits outweigh the additional work put forth initially.

5.0 CONCLUSION AND FUTURE WORK

Customer requirements and engineering specifications will influence the direction of the design in any product, so it is crucial to make the requirements as stable as possible to produce quality designs within a budget. Although it would be optimal for requirements and specifications to remain constant, many requirements will change during the evolution of a design. This may also require multiple iterations in the design process to account for all the requirements. These requirement changes can result in the disruption of the product development schedule, increase development costs, and fail to meet customer requirements.

Changing customer requirements can arise for numerous reasons and can occur during any stage of the design process. In an interdisciplinary design project, partners from varying disciplines work collaboratively to deliver a product design that will meet the evolving requirements of each discipline. Meeting product requirements for each discipline enhances the component interdependency. Evolving changes in one component engenders the changing of requirements and specifications of other components. The issue of designing under inadequately defined requirements in new product development can have similar outcomes. The development successes and failures of the BugID project provided the mechanical design team valuable insight into the process of designing under changing requirements. Product development strategies to cope with changing requirements and specifications were adapted from previous work and applied while developing working product prototypes for the project. In the application of the methods for design under changing requirements four main categories were identified:

1. Customer Interface
2. Iterative Design Process
3. Future Analysis
4. Change Tolerant Architecture

These four categories contain strategies that can be used throughout the design process. As a result, the time when these categories are applied during the design process may vary depending on the given project. The application of these categories during the BugID project is shown overlaid on the design process in Figure 9.

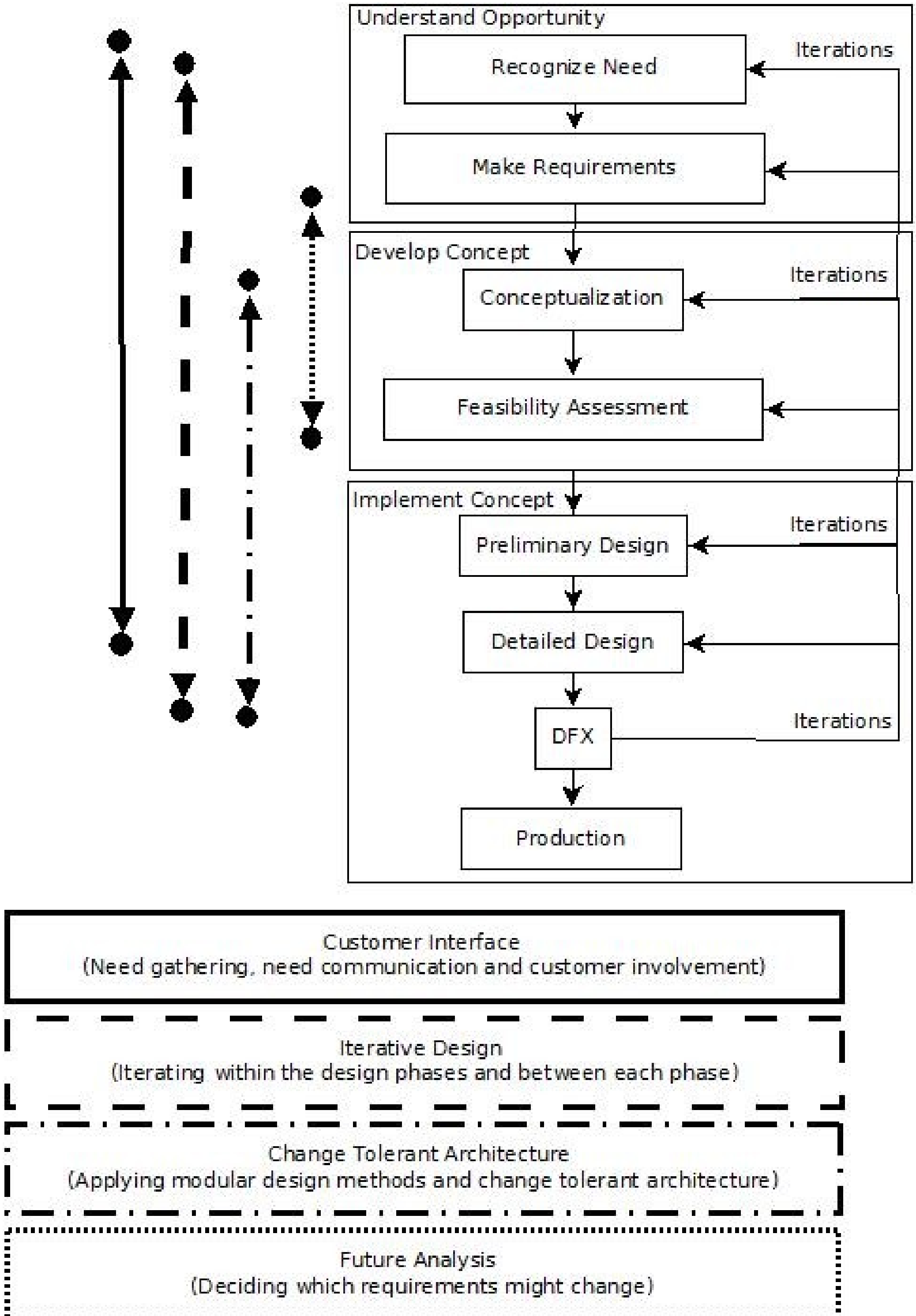

Figure 9: The design process overlaid with the four categories of design under changing requirements methods.

In the BugID project it became clear that these categories were interdependent and the four categories formed two sets of coupled categories seen in Figure 10. In the first coupling, effective communication in the customer interface lends well to an iterative design process. Conversely, it is hard to implement successful iterations if there is a lack in communication between the designers and the customers.

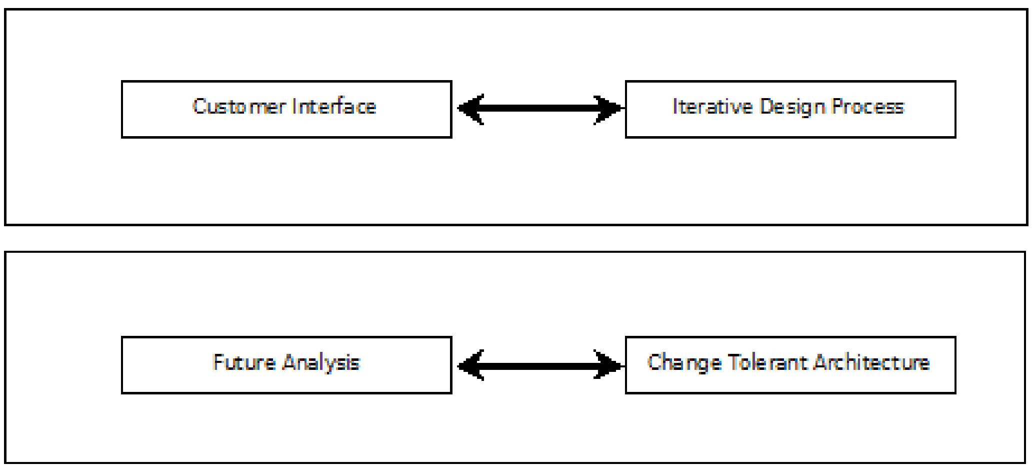

Figure 10: Coupled strategies for design under changing requirements

In the second coupling future analysis is used to identify possible changes that will be accounted for in change tolerance architecture. Correspondingly, it is hard to implement meaningful change tolerance architecture if the designers do not know what parts of the design have a high probability of changing.

Strategies for design during changing requirements will continually be applied to the development of mechanical design solutions for the BugID project. The immediate research plan is to utilize them to expedite the design cycle of the next generation of each BugID system. The project will also establish a more systematic design methodology for designing under changing requirements based on these strategies and with the next generation product design consideration will be given to evolving changes within the process. This methodology is anticipated to be applicable to many interdisciplinary product innovation scenarios, and will provide a process for dealing with changes in design.

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