Tacit Knowledge Acquisition in Advanced Manufacturing

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by

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Table of Contents

Abstract

Tacit knowledge (TN) is a kind of knowledge that is developed through repetition. Due to the inherent difficulty of acquiring TN in a timely manner, many manufacturing occupations struggle to fulfill positions with employees possessing the proper knowledge. Welding was selected as a case study. Via interviewing local welding shops, our team determined the variables important to a good weld and designed a teaching system that is used to accelerate the acquisition of welding TN. The concept of providing real time feedback can be extrapolated to several other areas of manufacturing.

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Executive Summary

The purpose of this IQP is to study tacit knowledge, knowledge gained through experience that is challenging to explain or teach to others through the many forms of communication, and make an attempt to shorten the time required to gain this knowledge. Tacit knowledge is present in many fields such as industry, arts, cooking, dentistry and healthcare, and can consist of many different forms of knowledge, skills, and abilities. Tacit knowledge can not be taught in the same way as traditional knowledge because it is a "hands-on" knowledge, or the "know-how" that is gained through long and challenging years of learning and practice, hence time is one the greatest hurdles to gaining this knowledge. This is largely due to the trial and error aspect associated with this knowledge, however acquisition of this knowledge can be accelerated by having real-time feedback and advice from another individual who already has experience.

For us to understand more about tacit knowledge and find a way to shorten the time it takes to gain this knowledge, we researched many industries that involve tacit knowledge acquisition, and ultimately welding was chosen as a case study. The reason that welding was chosen was due to its difficulty to teach and time required to learn, largely due to a foundation in tacit knowledge. Welding involves many "hands-on" processes that must be learned by doing it again and again. Not only that, welding is a prime example of an industry in dire need of new talent, due to the current welding shortage while the demand for welders continues to rise. There are many reasons that are causing the welding shortage: older and more experienced welders retiring, not enough new workers to replace them, and negative misconceptions of working in the welding industry by young people such as working in a dirty environment. The welding industry is well aware of these problems, and some solutions have already been taken by certain groups within the welding industry. These include things such as using robots/automatons to automate making parts, or training students using virtual reality (VR), but it is still not fast enough to combat the shortage. Hence, if we can successfully develop a way to shorten the time to gain tacit knowledge, it would not only help with the current issue, but it could also potentially help other industries that are struggling with tacit knowledge acquisition.

With the final goal of this IQP being to develop and test some type of system that would aim to accelerate the process of tacit knowledge acquisition, our team needed to collect data that could be used in the creation of a system that would help solve this problem. The first step for us was to develop a questionnaire that would acquire all data necessary for development of a system. The questionnaire would specifically target the differences present in the experience of a professional welder vs. the experience of a new hire or trainee. To do this, the questionnaire was split into two primary sections: "Educational History" to target the experience of the professional welder being interviewed, and "Workforce Experience" to target their current level of experience and any new hires they have interacted with or trained. With the general structure established, we further developed the questions to target specific information related to tacit knowledge. With the questionnaire completed, we sent it to the Institutional Review Board (IRB) for their approval.

Once we had the IRB approval, we moved on to our next step: conducting the interviews. For the interviews, local welders located around Worcester were chosen due to them being at a reasonable driving distance from campus. Over the course of the interview process, we were only able to interview three different local welding shops. While the sample size for the acquisition of data was small, there were still noticeable, important trends found within the interview results. Through these interviews, we found that repetition was the most important factor when it comes to gaining tacit knowledge. Welders would repeat hundreds of welds over the course of their career in order to gain the ability to manage a number of important factors of welding by feeling alone. These factors are position, which describes both the physical positioning of the welding tool and the distance the tool is held above the metal, heat management; speed of the weld; and the material properties of the metal or alloy used for the weld. Through these repetitions, they slowly understand the "feel" of what is "correct" and over these repetitions it is imparted onto them. To these welders, a "good" weld was visually appealing, with the right color and smooth, straight and consistent weld lines. When analyzed further, each quality of a completed weld is a consequence of the management of specific factors previously mentioned during the weld. The visuals are often affected by the speed and position. The strength of a weld is often due to the heat; the material must get hot enough to penetrate deep into the metal but not burn through. And managing the material properties are essential as each metal and alloy reacts differently during the weld. These are the factors that the welders are subconsciously thinking of when welding. For new welders, being able to manage the above factors without actively thinking of them is what causes welding to take so long to learn. Repetition is something that can be targeted by a system to minimize the number of time repetitions is required in order to manage these factors by feeling alone.

Based on the data that we collected, a total of five different designs were created to help transfer tacit knowledge to new welders by reducing the number of repetition new welders needed to perform. Although these five designs are merely concepts, each one has been carefully thought out with the important factors in mind. The first four designs had many positive aspects that helped with tacit knowledge acquisition. This includes things such as real time feedback for things such as speed, position, temperature through augmented reality (AR), an attachment to a welding torch that could give the same feedback through sensors, and more, but they also have many negative aspects such as high cost, weight, etc. The final design that we chose is called the Internal Mask System. The Internal Mask System is a device that can be attached to a welding mask using glue or a double sided tape. There are three parts to the device: a torch mounted sensor, a live feedback display, and an external configurator module. The live feedback display would have an analog arrow display for things such as temperature, speed, and angle from a sensor attached to the welding torch. The external configurator module would allow the user to switch things such as metal and thickness. The data obtained from the welding duration can be displayed as graphs in a program by uploading it through a USB. The program would then give a score based on the precision and accuracy of the welder. Overall, this system would be able to give new welders easy to understand feedback in real time without distracting them from welding. However, this system is not intended to replace the need of instructors because it cannot teach things such as the fundamental knowledge of welding, rather, this system should be used in tandem with an instructor’s feedback to teach new welders as quickly and as efficiently as possible.

The impact of tacit knowledge on everyday life is substantial, and this type of knowledge is the foundation of countless skills used every day. This knowledge is something that can only be acquired after countless hours of practice and training, and not something that can just be simply learned through studying or literature. Our goal for this IQP is to create a system that can shorten the time it takes to gain tacit knowledge, and the Internal Mask System fit the qualifications best. If it is successful, it would not only reduce the training time of new welders, but also possibly prevent future scarcity of welders. However, this study does have its limitations, one of the main issues would be the small sample size of only three local welders. With the small sample size, other types of welding industries were not possible to be explored in our research. Our data only represent a small percentage of the entire welding industry, hence additional factors that could affect the welding process such as humidity or ambient temperature at different locations needs further research. For future iterations, we recommend spending more time on gathering data at the interviewing stage. For future iteration, we recommend two things: developing and testing the Internal Mask and spending more time on gathering data at the interviewing stage. In section 4.5 of this report, a picture of the Internal Mask and a detailed explanation of its capability is discussed. With that information, we believe that developing a prototype would be possible. In terms of spending more time gathering additional information during the interview stage, more data on parameters such as factors that affect a welding work piece would give a better representation of the training method of the welding industry, which could provide additional insight for gaining tacit knowledge. If more research could be done on tacit knowledge, it would not only be applicable to the welding industry, but also other manufacturing industries that require faster tacit knowledge acquisition.

Table of Authorship

Editing	**Ryan, Sroka**
Title Page	**Ryan**
Section 1. Introduction	**All**
1.1 Tacit Knowledge	Ryan, Sroka, Christian
1.2 Welding Industry	Ryan, JR, Christian
Section 2. Background	**Sroka, JR**
Section 3. Methods	**Sroka, Ryan**
3.1 Research on Tacit Knowledge	Sroka
3.2 Development of Questionnaire	Ryan
3.3 Development of Training System	Sroka
3.4 Methods Conclusion	Sroka
Section 4 Findings	**All**
4.1 Introduction	Ryan
4.2 Interview Results and Analysis	Ryan
4.3 Preliminary Designs	JR
4.4 Design Decision Discussion	Christian
4.5 Internal Mask System	Ryan
Section 5. Conclusion and Recommendations	**Ryan, Christian**
5.1 Summary	Ryan, Christian
5.2 Limitations	Ryan, Christian
5.3 Recommendations	Ryan, Christian
5.3 Wider Implications	Ryan
Appendix	**All**

List of Figures

List of Tables

Section 1. Introduction

Tacit knowledge is defined as knowledge gained through experience. It is a type of knowledge that is notoriously challenging to explain or teach to others through communication alone. This type of knowledge is present in many fields and applications such as the arts, cooking, medical, and manufacturing. It is commonly known as “hands-on” knowledge and the proverbial “know-how” that is gained most often through long, challenging years of learning and practice. This study targets the underlying challenges presented by the process of tacit knowledge acquisition. Industries that are reliant on tacit knowledge often struggle to find an adequate amount of employees, with some industries seeing a decline in their work force. For this study, the goal of improving the rate at which tacit knowledge can be learned will be the main focus.

1.1 Tacit Knowledge

As a collection of knowledge, skills and abilities, tacit knowledge cannot be fully taught through literature alone and must include physical practice. The inclusion of this physical practice during the training process is what allows the student to apply what they have learned and observe the outcome of their actions. With the help of an instructor, the student is able to observe where they need improvement and what changes they must make to do so. By quickly identifying the mistakes made and subsequently informing the student of the improvements needed, the student is able to combine the tactile feeling of the mistake with the knowledge of what happens as a consequence to form an impactful experience that will contribute to their tacit knowledge. The time requirement to become proficient within an industry which relies on tacit knowledge is great, often taking between several months to multiple years, depending on industry standards. Frequently, this training process is the largest limiting factor for employment rates. Facing challenges in the consistent acquisition of experience, the training process for tacit industries is slowed, resulting in long periods before a student can be considered proficient in their industry. This increased training process affects industries like welding which faces a future scarcity of workers.

1.2 Welding Industry

With the decline of suitable employees within the welding industry, the need for people to learn skills faster has become essential. In an attempt to improve current training methods, alternative systems have begun to be considered. These alternative methods utilize new technologies like virtual reality and augmented reality to simulate the welding process. Due to the relatively early stage of these technologies, they lack the necessary capabilities to be effectively integrated into a proper training system. Without the ability to return tactile feeling students are unable to acquire tacit knowledge effectively. Because of this, most current tacit knowledge acquisition teaching methods rely on traditional methods such as workshop practice. For the purpose of this project, the welding industry was used as a case study. With almost twice the number of welders retiring as they are joining, welding is projected to face a scarcity that could greatly impact the majority of modern infrastructure and manufacturing. If such a scarcity becomes a reality, production will be reduced which in turn will slow economic commerce, while vital infrastructure will face infrequent maintenance and repair. The reasons for this disparity stems from several variables, ranging from training times to societal perception. In an attempt to mitigate the growing concern, our team delved into the learning process of welding with the goal of creating a system upon which the training process of welding is capable of being optimized. Through this research our team discovered one of the essential training processes: repetition. With repetition identified as our target for improvement, our team created several theoretical teaching devices that utilized our findings to possibly improve the teaching process for welding.

Section 2. Background

Tacit knowledge covers a broad, expansive amount of knowledge. It is seen in the execution of complex tasks that require any amount of training to faithfully perform. Tacit knowledge is present in anything from riding a bike to the polishing of automotives, and can be seen in hundreds of other tasks in widely different areas of life. Tacit knowledge is unique in the fact that it cannot be taught in the same way as traditional knowledge. There is no lecture to teach a child how to ride a bike. The transfer of such a skill is taught through experience. Tacit knowledge is built through these trial and error experiences. The acquisition of this knowledge can be accelerated by having real-time feedback and advice from another individual who already has experience. Tacit knowledge also takes significantly more time to learn as this trial-and-error, feedback-oriented learning method tends to have large gaps in time between attempts and involves small corrections based on outcomes of previous iterations. This time cost to develop tacit knowledge is one of the greatest hurdles to gaining tacit knowledge, especially in a world that demands efficiency.

Human behavior largely relies on tacit knowledge in order to execute complex actions. Rasmussen et. al. decomposed behavior into three main categories: skill, rule, and knowledge.[1] Skill-based behavior are behaviors that can be executed without conscious thought and is typically seen in slow, methodical tasks like drawing, assembly, and simple motor functions like picking up a glass or touching one's nose. Rule-based behavior is guided by some stored selection of rules, typically learned through guidance. This guidance can be from another person, such as in the case of training or reading instructions, or self-learned through trial and error. Knowledge-based behavior occurs in a situation that is entirely unfamiliar or does not have a direct rule or set of rules that can apply. Knowledge-based behavior has an individual lean on similar experiences, formulate potential plans, weigh those plans against one another, and determine the best course of action to resolve the situation. It is the highest level of behavioral patterns. For each of these behaviors, people rely on signals, signs, symbols, cause, and reasons to select and execute a procedure.

In all three behavioral types, tacit knowledge is present. Skill-based behavior utilizes tacit knowledge that is so well refined that it no longer requires conscious thought to execute. Once one learns how to pick up a glass properly, the behavior can be executed with very little conscious attention. It may take an infant a few attempts to learn how to coordinate themself to grip the glass and lift, but once they make the minute corrections to their procedure they no longer require much thought to grip and lift the cup. Within rule-based behavior, the rules and procedures are determined through past experiences that resulted in a successful outcome. While driving a car, if there is a red light in an intersection, the proper behavior is to stop. The rule used to derive an action based on the signal is "if red, stop." This knowledge is not immediately known and must be learned through the teachings of others or experience driving. On occasion, rule-based behavior does toe the line between tacit and explicit knowledge. A person can be taught "if red, stop" in a classroom or lecture setting. However, rule-based knowledge also applies to rules derived from personal experiences instead of those explicitly stated. Learning how far to lean on a bike to correct balance is not something that can be taught in a classroom. Rather, it must be learned through trial and error. Rule-based behavior can be both explicit and tacit knowledge for this reason–elements of rule-based behavior can be taught while other portions need to be learned through experience. Within knowledge-based behavior, the decision is decided through logic and reasoning, and is usually applied to situations that are unknown rather than situations that can be related to direct rules. In these unfamiliar situations, individuals fall back on the knowledge they have to similar situations to derive an outcome that is best suited for the case. A plumber may run a diagnosis on a blocked pipe to discover the source of the blockage. They must then rely on previous experiences of unblocking pipes to account for the specific variables of their client's plumbing system–the space available, the orientation of the pipes, the location of the blockage, the angle at which their tools can reach the pipes–to conduct a successful operation. Rather than one specific rule followed, "if red, stop," knowledge-based behavior requires critical thinking and associating previous experiences to the current situation. Rule-based and knowledge-based behavior is far more common in work environments than in everyday life due to the complexity of behaviors needed to be executed during employment.

Because the scope of tacit knowledge is so wide, the focus of our research is narrowed to the manufacturing world. Tacit knowledge is present in a large number of manufacturing occupations, especially those with non-standardized work that needs adaptation like repair and polishing. Tacit knowledge was investigated in a pair of case studies by Johnson et. al, where researchers used the same behavioral breakdown set forth by Rasmussen et al.–skill, rule, knowledge–to categorize behavior observed during visual inspections of aerospace component production and component maintenance.[2] Both cases produced similar outcomes: for each step of the process, rule-based behavior was the most commonly executed. As previously discussed, rule-based behavior is a kind of tacit knowledge, and the frequent use of this rule-based behavior in the workplace demonstrates why tacit knowledge needs to be studied. It is simply used so frequently in the workplace that the development and acquisition is a vital part of employment. Skill- and knowledge-based behaviors were also seen demonstrated in this case study, however the frequency was far less than that of rule-based behavior.[2] The increased difficulty of a behavior becoming skill-based and the repeated motions of analyzing the similar or identical aerospace parts are possible explanations for why these two categories of behavior are less frequent than rule based behaviors. Even so, all three categories are considered tacit knowledge and their use in the workplace shows that they should be studied in depth.

Though the acquisition of tacit knowledge is undoubtedly one of the most remarkable abilities in human behavior, the time it takes proves to be a challenge for expanding demand. Workforce shortages, such as those occurring from the COVID-19 pandemic and failure to retain talent[3][4], and increased demand for machining products in an expanding market[4][5] make it necessary for individuals to learn skills faster in a system that functions best with time. To reduce the time and cost, some training methods have looked into using virtual/augmented reality or welding simulators to help trainees become familiar with the techniques or machines needed for work. However, utilization of this technology has not yet reached its full potential [6] or cost high amounts of money to be used by technical schools with a small budget or smaller welding locations who train their employees in-house.[7] Training remains challenging and time consuming. In a modern world demanding efficiency, the amount of time that it takes to thoroughly build, hone, and perfect skills for applications of tacit knowledge proves to be a tremendous roadblock for several areas of manufacturing. The simultaneous abstractness of tacit knowledge and the time it takes to consume both bar rapid acquisition of machining skills. The aim of this project is to take the first steps towards accelerating that acquisition process, with a specific focus on welding.

Welding was chosen as the method of study for this IQP due to the prevalence of tacit knowledge in the workforce. Furthermore, welding is a prime example of an industry in dire need of new talent, weakened by a current welder shortage while the demand for welders continues to rise. According to the American Welding Society (AWS), due to industry growth and attrition in the current workforce, about 360,000 new welders are needed by 2027, or roughly 90,000 new welders every year [8]. Currently, there are approximately 770,000 welding professionals as of 2023, with more than 155,000 approaching retirement [8]. This IQP hopes to find a solution to the welding shortage problem by trying to reduce the time it takes new welders to gain tacit knowledge.

There are many factors that contribute to shortage. First, many older and more experienced welders are retiring, and there are simply not enough new workers to replace them. As explained previously, gaining tacit knowledge takes a long period of time until someone becomes proficient enough to work. As reported by the AWS as of 2023, more than 90% of the current welders are over the age of 25, with about 47.5% of welders being 25 - 45 years old [8]. In addition, *Manufacturer' Monthly* claimed that the U.S. will face a shortage of 500,000 welders by 2030, and 250,000 welders by 2050 for Japan [9]. According to the New England Institute of Technology, welding programs take approximately a few weeks or up to 6 months to complete, with up to 18 months to 2 years to get an associate degree [10]. In addition, apprenticeship could possibly take years if someone does not have prior welding experience [10]. YesWelder stated that apprenticeship could take as little time as 12 months, or up to 6 years [11]. In these welding programs, new welders will learn things such as basic welding process and procedures, different techniques, equipment safety codes, and more [12]. However, Charter College has also stated that "...welding can be a lifelong career or passion where you learn something new every day" [11]. With welding being a career where welders could continue to hone their skills year by year after completing their programs, and also acquire new knowledge, it can be hard to judge how long it takes welders to become "proficient" enough to work. Someone's perception of a welder could possibly be biased if they were to compare the skills of a welder who has continued improving their skills for years to someone who had just finished their training program. If many people in the welding industry judged welders training for years as the standard of being "proficient", and deemed the new welding graduates for not being "proficient" enough, it is no wonder that there is a welding shortage. Nevertheless, what is currently known in the welding industry is that the training time for new welders is simply not fast enough. Weld Australia has stated that aging welders will soon retire, and it will be impossible to fill the position with new welders given the increase in demand for them [13]. With how long it takes to train new welders, old welders are retiring faster than new welders can replace them.

Another factor that could contribute to the welding shortage problem is misconception of working in the welding industry by young people. These misconceptions include things such as lack of career growth, compensation being lower than other industries, work being repetitive, monotonous, or underpaid, and that welders work in decrepit, dirty environments [13]. First, according to YesWelder, metal fabrication that is used in welding is also widely used in the aerospace, construction, and automobile industry, and that "...welding skills can be applied to various industries, so you can easily switch from one industry to another with little to no need for training" [11]. Second, similar to many other careers, compensation is completely dependent on things such as experience, employer, industry, and more [11]. A new and inexperienced welder would obviously earn less than an experienced welder who had been in the industry for many years. YesWelder stated that the lowest 10 percent of welders' annual salary is about $35,380, and the highest 10 percent is about $68,750 [11]. Certain welders that work in harsh conditions such as underwater and rig welders can earn over $100,000 annually [11]. While it is not completely false that the salary for welders is lower than some industries, with enough experience, it is possible to increase it similarly to many careers out there. The argument of welding being repetitive and monotonous is completely dependent on the person. This argument on the whole could be applied to every job that a person has no interest or passion in working. As for the working environment, the U.S. Bureau of Labor Statistics (BLS) explained that welders work in both indoor and outdoor areas, and sometimes in confined areas with sparks and glares high off the ground or on scaffolding [15]. The BLS also stated that welders may be exposed to hazards such as fumes, hot metals, sparks from welding and more, and thus it is important to strictly follow safety procedures such as wearing protective equipment [15]. Things such as sparks and hot metals are unavoidable because they are a part of welding, so this working environment should be one of the main things that people should consider before working in the welding industry.

The welding industry is well aware of these problems, and some solutions have already been taken by certain groups within the welding industry. The AWS have stated that the main reasons for the welding shortage are industry growth, and the growing demand of new talents

[8]. YesWelder gave reasons such as industry growth, age, misconceptions, and technological improvements [11]. When it comes to solutions to these problems, things such as robotics have been used to deal with the welding shortage. FANUC America has developed a robot that has a range of 7 kg to 25 kg payload, and 911 mm - 3123 mm in reach capable of welding operations such as MIG welding, TIG welding, plasma and laser cutting [16]. MIG welding is a type of welding where the process uses "...constant voltage power supply to create an electric arc that fuses the base metal with a filler wire that is continuously fed through the welding torch. At the same time, an inert shielding gas is also fed through the gun, to protect the weld pool from atmospheric contamination" [14]. TIG welding is a welding process that uses tungsten inert gas to create welds [19]. The process "...joins metals using a non-consumable tungsten electrode while protecting the welding area from atmospheric contamination with an inert gas such as argon" [19]. According to UNIMIG, TIG welding is the hardest welding method to learn due to " the coordination between moving the torch and feeding the rod in at the same time" [20]. YesWelder also stated that robotics might make "…welding more appealing to young people raised on technology" [11]. With the creation of robots, it is easier for companies to create welds using MIG or TIG welding, however, these robots can't teach new welders these two techniques, so it will still take time for welders to learn them. If tacit knowledge acquisition of these two techniques or techniques that are similar can be shortened, then it would greatly benefit the welding industry.

Another method is Virtual reality. Tulsa Welding School has been using Virtual reality to create an immersive welding experience without the use of real equipment and hazards, and also saving real materials [16]. Virtual reality training allowed the instructors to keep track of student's metrics such as body position, arc speed, weld quality, and machine setup [16]. This training also helps with things such as right welding material, optimal gas flow, correct voltage and amperage. According to Tulsa Welding School, they assign scores to things such as speed and accuracy to make it similar to video games, and it motivates students to compete with one another [16]. However, these solutions come with their own problems. According to The Belgian Welding Institute, they have stated that due to the increase for automation/robotics to replace welders, the demand for people who both have welding knowledge and programming skills are also needed due to the complexity of the robot, which creates further problems [8]. Similarly, YesWeld said that "Robots still need welding operators, programmers, or certified welding supervisors to run them" [11]. When it comes to virtual reality welding, ABW technology stated that welding virtually can not only cause headaches, but also that it is not the same as welding in real life, and that it is only a companion to real world hands-on experience [18]. Another thing is that it is intangible, meaning that the things you weld in virtual reality will stay there, so there is nothing that can be shown physically in the real world [18].

While tacit knowledge acquisition overall will help deal with the welder shortage issue, one method to further decrease the demand could be to develop a system that is able to transfer tacit knowledge to machines through machine learning in the future. Although this would solve the welding shortage problem, it could also take away current welding jobs if it is proved to be too effective. For example, small local welding shops in towns/cities could potentially lose customers because machines would be faster at making parts at a larger quantity. Even though this is not a problem now, it is something that companies that utilize robotics have to take it into consideration in the future.

Although there are some strategies to decrease the demand caused by the welder shortage problem, it is clearly not nearly enough to fix the issue. There are many factors that contribute to the problem: old welders retiring, not enough new welders, time to teach/learn, and misconceptions. Although this IQP wouldn't be able to fix every issue relating to the welding shortage, it would definitely be a step forward. Furthermore, shortening tacit knowledge acquisition time would not only be applicable to welding, but also other types of careers that involve any types of hands-on skills learned through experience (i,e. polisher, technicians, etc.). Hence, a criteria for a successful project would mean figuring out a way that new welders are able to acquire tacit knowledge in a shorter amount of time compared to if they were to learn normally through apprenticeship.

Section 3. Methods

The initial goal of this project was to develop and test a system that would aim to accelerate the process of tacit knowledge acquisition, specifically in the welding field. The intent was that the system could be applied to a number of different fields requiring tacit knowledge, with welding as our case study. To develop this curriculum, our team followed the following procedure: First, conduct research on current fields requiring tacit knowledge, narrowing our focus to one case; Then, develop and utilize a questionnaire to interview local welders and welding educators in the Worcester, Massachusetts area to address specific questions related to the acquisition and usage of tacit knowledge; and finally analyze the responses from the interviewed welders to create a system that could facilitate accelerated tacit knowledge acquisition for new welders in training. In this chapter, we detail the methodology used throughout this process and the intended use of the results from each process to form a complete analysis.

3.1 Research on Tacit Knowledge

In order to quantify and understand the specifics of a broad term such as “tacit knowledge” our team began by conducting literature searches on tacit knowledge using online resources. The goal of this section was to observe how tacit knowledge was used across multiple different areas of manufacturing, with a focus on areas that have not yet seen great success in machine-conducted tasks. Because of the broadness of the category, our team needed to collect information to narrow the scope of the project. Our research was focused on the following categories, each of which having a question or series of questions that would provide some context to the category:

1. *Presence of Tacit Knowledge in the Workforce*. How frequently was tacit knowledge used in everyday work? Was it prevalent enough to be noteworthy?
2. *Necessity to Accelerate Acquisition*. Does the workforce have a need for accelerated tacit knowledge acquisition? Is the demand for a product enough to warrant a modified system?
3. *Scope*. Are there enough individuals currently involved in the workforce or education that would benefit from the development of a new system?

4. *Relevancy to Manufacturing or Mechanical Engineering*. Does the area have any relation to manufacturing? Any relation to mechanical engineering?
5. *Accessibility*. Are there locations accessible to the researchers where they can collect relevant information to design and test a curriculum?

The intent behind researching with these categories was to find a case study to focus on. The ideal case would meet the criteria as follows:

1. Tacit knowledge is used almost if not every day during work.
2. The workforce has a significant need for accelerated learning. Demand is high enough that the workforce market is not likely to collapse.
3. A high number of individuals are currently employed or seeking to learn to acquire the skills to enter the workforce.
4. The area is directly related to manufacturing or mechanical engineering.
5. There are a number of locations present and accessible for research to be conducted in person, including a location to test developed systems.

As the research team conducted independent searches on the subject of tacit knowledge, there were many emergent areas. These areas included blacksmithing, automotive polishing, machining, welding, and dentistry. The team then shared their collective information and began to filter the compiled information utilizing the categories described above. Dentistry was eliminated due to its lack of relation to mechanical engineering or machining. Blacksmithing was eliminated due to the significantly smaller demand for human work. Machining was eliminated due to the lack of accessible locations for our research team to conduct interviews and observations. This left the team with automotive polishing and welding. Between the two, our team chose welding because of the presence of a training program at the nearby Worcester Technical High School that could be potentially used to test curriculums. There were also a number of local welding locations that our team could conduct our research in. As such, welding was selected for our case study and the team began to develop the method to collect data.

3.2 Development of Questionnaire

With welding selected as our case study, our team needed to begin collecting data that could be used in the creation of a system that would accelerate the process of learning tacit knowledge. This data would entirely be in the form of interview results, therefore it was critical to construct a questionnaire such that we acquire all data necessary for development of a system. In order to accomplish this, it was first necessary to identify what guidelines must be followed in the development of this questionnaire. The first most important guideline, due to the very nature of tacit knowledge, was that none of the interview questions could directly refer to tacit knowledge. This concluded for two primary reasons. First, tacit knowledge is not common knowledge. While everyone implicitly has tacit knowledge in some form, few know the term itself. If any question were to refer to tacit knowledge, the results would likely be skewed or unusable, limited entirely due to the interviewee's own understanding of tacit knowledge or lack thereof. Secondly, tacit knowledge is difficult to discuss by nature, a fact of which is the motivation for the project. Therefore all questions had to allude to tacit knowledge in order to acquire useful data, but the questions had to be crafted such that they were targeting specific facets of tacit knowledge more easily answered by the average interviewee. This primary guideline leads directly into the next, that each question had to be written to extract the specific usable information in accordance with the previous guideline. Since tacit knowledge could not be directly referred to, as per the previous guideline, this information must paint an accurate picture of the concept when put together. So, the larger ideas of tacit knowledge were separated and condensed into smaller sections for the sake of these questions, in order to be more approachable. In short, the important takeaways was as follows:

1. The time it takes to enter the workforce.
2. The most challenging technique(s) for a welder.
3. The most impactful and/or common teaching methods.
4. Whether or not the above information differs for new or established welders.

In combination with the above takeaways, there is much more information that could be used to round out the results, leading to a large amount of possible questions to ask during an interview. Because of this the following guideline was established, that the interview would have to conform to the typical 15-20 minutes of similar scientific surveys. As such, the developed questionnaire had to include only very specific, focused questions in order to acquire all the necessary data to develop the theoretical system.

With the above guidelines in mind, the questionnaire was developed with specific organization to maximize efficiency and efficacy of the interview. The first goal was to specifically target the differences present in the experience of a professional welder vs. the experience of a new hire or trainee. As such, the questionnaire was split into two primary sections: “Educational History” to target the experience of the professional welder being interviewed, and “Workforce Experience” to target their current level of experience and any new hires they have interacted with or trained. With the general structure of the questionnaire established, the questions can be developed in order to target the specific intended information. From here, many questions were drafted, creating a long questionnaire that, while achieving the first two guidelines, failed the third. In order to retain guideline 1 and 2, but conform to guideline 3, questions were combined in order to streamline the interview and eliminate any questions targeting adjacent but ultimately unessential information. The result was a questionnaire that achieved all of our guidelines, containing specific, targeted information that was ready for interviews following an Institutional Review Board (IRB) approval (IRB-24-0319).

Once we had IRB approval, we could move forward with the interview process. Local welders were chosen and called to schedule interviews. Each interview followed the same structure. Our team met within the interviewee’s shops, where only the interviewee(s) were present. Of our team, there was one “proctor” who conducted the interview as well as handled any communications outside of the interview with the interviewee. The rest of the team who could attend were “scribes” who took detailed notes during the interview. No audio or identifiable information was collected during the interviews. Following the interviews, all notes were transcribed and stored digitally to be accessed and analyzed at a later date, but destroyed when the project was complete. This collected data was analyzed, and any patterns, strategies and techniques which would be important for the development of a curriculum were identified. Based on these patterns, a secondary questionnaire was developed in order to have follow up interviews to focus on these notable emerging trends, following the same protocol as the initial round of interviews. We revisited two of the three original interviewees and collected additional results, recorded and stored digitally as before.

3.3 Development of Training System

Once the information was collected through the welders, our team needed to develop the system that we would be implementing into current welding training methods to accelerate the tacit knowledge acquisition. However, securing the interviews took far longer than our team anticipated, which drastically shortened the time frame we had to create and test this experimental system. Because of the significantly shorter deadline, our team concluded that with the remaining time we had in the project it would be far more reasonable to focus our efforts into creating a *theorized* system that would not be tested on welders currently in training. This theorized system would follow the same development techniques that our real system would have, with the exception of missing the testing and adjusting stages in order to prove whether or not the system is effective.

In order to develop our system, we followed another set of guidelines that would help guide formulation of different elements. Our team began designing these guidelines with the assumption that there would be quantitative and qualitative data collected during the welding process that would be provided to the user as they learned. The quantitative data would come from physical sensors that would detect properties such as temperature, position, velocity, and time. The qualitative data would come from devices such as audio or video recordings, or verbal statements from the user as they worked. The guidelines produced for our system development are as follows.

1. All data recorded is directly related to acquiring tacit knowledge in welding. (REL)
2. Data collected is useful to acquire tacit knowledge in welding. (USE)
3. The system provides real-time feedback to the user. (RTF)
4. The feedback provided is understandable and/or has a user-friendly interface. (UI)
5. The system is practical. (PRAC)
6. Any recorded data must be of a high enough quality or collected in an organized way such that upon playback or analysis the data can be understood. (HQ)
7. The user is given full control of the data collected, especially considering personally identifying information such as video or audio recordings. (CON)

These guidelines aimed to keep the system as user-friendly, useful, and effective as possible while still accelerating acquisition of tacit knowledge. Before creating some hypothetical systems, these guidelines were also modified into a Pairwise comparison chart to determine their importance to the design. The acronyms following each of the guideline statements are used to represent each guideline in shorthand for the Pairwise comparison chart. The Pairwise chart compares each row to the remaining opposing guidelines. The rows are given a score based on whether or not they are more or less important to include in an optimal system. These scores are totaled to determine the weights of the guidelines for the Pugh analysis.

	vs. REL	vs. USE	vs. RTF	vs. UI	vs. PRAC	vs. HQ	vs. CON	Totals
REL	X	0	1	1	0	1	1	4
USE	1	X	1	1	1	1	1	6
RTF	0	0	X	1	0	1	1	3
UI	0	0	0	X	0	1	1	2
PRAC	1	0	1	1	X	1	1	5
HQ	0	0	0	0	0	X	1	1
CON	0	0	0	0	0	0	X	0

Table 1: The Piecewise comparison chart ranking the seven guidelines.

To properly conduct a Pugh analysis using the weighted guidelines, it was necessary to determine the baseline for each of the guidelines that system designs could be compared to. The baselines for each individual category are described below.

REL. All data sets collected are directly related to the acquisition of tacit knowledge in welding.

USE. All data sets are useful for the acquisition of tacit knowledge in welding.

RTF. The system provides feedback in at most half a second.

UI. The system has a user-friendly interface.

PRAC. The system can be reasonably used in both technical school environments and welding shops. This category also includes installation, pricing, and ease of use. Installation is simple, the system has a moderate cost, and the system is easy to use.

HQ. Any collected or recorded data is stored in a format that is compatible with text-based file editing programs. If the recorded data is stored in a format that is specific to a software, the software includes a feature to export data to a format that is compatible with text-based file editing programs.

CON. The user can easily locate and delete any recorded data with little effort.

During the Pugh analysis conducted and detailed in the findings section, our preliminary designs were compared to these baselines and weighted with the scores determined through the Piecewise analysis to determine the most promising result. Development of the prototype systems to be subjected to these design analysis methods would occur once the interviews had been completed and relevant primary source information was gathered.

3.4 Methods Conclusion

Through a combination of research, questionnaire drafting, interviewing, and design formulation and evaluation, our team developed a thorough process that would facilitate the creation of a system that aimed to accelerate the acquisition of tacit knowledge related to welding. The questionnaires formulated in section 3.2 and the weights derived from the Piecewise comparison chart in section 3.3 would be used to create and rank preliminary designs detailed in section 4.

Section 4 Findings

4.1 Introduction

Using the developed questionnaire, the next goal was to interview as many local welders as possible in order to draw conclusions based on prevalent trends and use them to design an effective system to minimize the time required to acquire the tacit knowledge so embedded within the welding industry. Over the course of the interview process, we were able to interview three different local welding shops. While the sample size for the acquisition of data was small, there were still noticeable, important trends found within the interview results. In short, the most relevant trend was the importance of repetition throughout the learning process, the act of repeating hundreds of welds over the course of a student's career in order to gain the ability to manage a number of important factors by feeling alone. These factors are position, describing the positioning and angle of the welding tool during the weld and the distance the welding tool is from the material; heat management; speed of the weld; and the material properties of the metal or alloy used for the weld. Agreed upon by the interviewees, more often than not managing these several variables produces “good” weld. Using these trends, we developed a proposed system targeting this important learning process, with the goal of minimizing the number of required repetitions to learn how to manage these factors using an automated feedback system.

4.2 Interview Results and Analysis

Three initial interviews took place at three separate welding shops. Each interview had one participant, with the exception of the first interview site; while there was only one primary interviewee, two participants answered questions. Each interview lasted 15 to 30 minutes, depending on the engagement of the interviewee. The first interviewee had been welding for 24 years, with the majority of their formal training taking place at technical high school. The interviewee briefly explained this training, which described a gradual shift from the slow and methodical gas welding, to eventually using fusion welding. The second interviewee had been welding since they were 10 years old, with no formal training. They learned welding largely through family members in the field, and got a certification far later in life over the course of only 6 months, a process hastened due to their previous experience. The final interviewee had been welding for 40 years and, similarly to the first interviewee, began their career welding in trade school, which had alternating weeks of standard classes and workshops, where they focused on welding and general metal fabrication. In addition to trade school, this interviewee also had family members in the welding industry, who they learned from while in trade school. Immediately, there were trends present amongst the interviewee's answers. It became clear that many welders, including all of the interview participants, had been welding for many years, and many also had familial ties to the welding industry which served as an early introduction to the industry.

When discussing the challenges of welding, both while learning and in the professional industry, many more trends were immediately apparent. The most common challenges at this point were positioning and heat management during the weld. In the first interview, the interviewee described how the pooling and melting of metal while welding was particularly challenging and important to manage. This added additional challenge for positioning, particularly for upside down welds which had to be done faster to decrease melting. In the second interview, the interviewee described how "keeping the flow going" was challenging. When questioned further they elaborated, explaining that keeping straight, clean and visually appealing welds was particularly challenging. The final participant explained that different materials, particularly non-standard, can be challenging to work with. They described that metal and alloy properties in addition to the thickness could greatly affect how these metals and alloys react during the weld, adding increased challenge and intricacy to the welding process, especially if the alloy used was uncommon. Additionally, all interviewees stated that TIGwelding was the most challenging type of welding for the reasons they stated above as well as the complexity of a tig-weld machine and setup. These trends suggest that a handful of important factors, such as material properties, heat, speed, and positioning are highly impactful, and managing these factors are essential to create a "good" weld.

The most prominent trend amongst the results of this first round of interviews was the importance and role repetition played in the training of both the interviewees and their experience with new hires and trainees. Every interviewee explained that repetition, the process of repeating hundreds of welds each day, was the most effective process to learn welding. For the second and third interviews, who have experience with trainees, they explained that they also used repetition to teach these new hires. For each interviewee, the repetition process was largely the same. A welder in training would make hundreds of welds in any given day, and between each iteration, the instructor would provide feedback, which would be used for the next iteration and ideally, a “better” weld. During the third interview, the interviewee went in more detail describing this feedback process. The feedback was largely focused on mistakes made in the last iteration, where the instructor would point out what doesn't look right and, if the case permitted it, point out what the welder in training did wrong, and from the feedback the trainee would attempt to correct the mistake and push forward. This process would repeat over countless iterations until the welder in training can consistently make “good” welds. However, they also explained that there is a balance to this process, and it is just as important to give positive feedback to the trainee, such that they also know what they are doing right.

In order to acquire more data on the trends that emerged from these first three interviews, two followup interviews were conducted, the biggest focus of which was repetition and why it was so impactful to a learning welder. Again, the interviewees had common answers. Naturally, feedback is the common guide through this process, usually from the instructor. Feedback is how the trainee knows when or when not to change their technique through each iteration. They explained that it is a process that with each iteration the trainee grows more familiar with what is “right” and gets closer to the ideal weld. Through these repetitions, they slowly understand the “feel” of what is “correct”. To streamline this acquisition process, two questions are proposed: what is to be changed through each iteration on the path to the “perfect” weld? What is the information held within these subjective terms of “right” and “correct”? Explained by the interviewees, the welders in training change their technique by the feedback of an instructor in order to manage certain factors which affect the quality of a weld. Many of these factors were already discussed in previous interviews, such as heat, positioning, speed and the material properties. Other more unique answers, such as the color of the final weld and the sound made during welding could also be simplified further to one of the above qualities. Sound was often a consequence of positioning and speed. The color of the metal was due to the heat, and watching the color was this interviewee’s method of managing heat. However, these interviews did expand our understanding of the factors discussed in the first interviews. Distance from the metal was a very important quality of position. Managing the energy output of the welding tool, such as the current for TIG welding, was a method to manage the heat. Materials, which react differently based on their properties or thickness, could require more or less heat to be most ideal. These variables are summarized below.

Position. Describes the physical location of the welding tool on the work surface, including the angle of the tool's rotation and the distance the tool is from the material.

Speed. Describes the speed the tool is used and moves across the material.

Heat. Describes the buildup of heat within the metal during welding.

Material Properties. Describes the physical qualities of the material used for the weld, including the physical properties of the metal or alloy, such as density, and the thickness of the material.

Through these interviews, the qualities of a good weld were apparent. A "good" weld was visually appealing, with the right color and smooth, straight and consistent weld lines. It was a strong weld that penetrated deep into the material. But when analyzed further, each quality of a completed weld is a consequence of the management of specific factors during the weld. These factors, gathered from the above data, are heat, speed, position, and material qualities. The visuals are often affected by the speed and position. The strength of a weld is often due to the heat; the material must get hot enough to penetrate deep into the metal but not burn through. And managing the material properties are essential as each metal and alloy reacts differently during the weld. These are the factors which every welder manages during each and every weld. They are the factors that students are taught through repetition, over countless iterations, to manage by feeling alone. However, management of these factors is not the only thing a new welder must learn. As described by the interviewees, there are general order of operations and a "procedure" to follow in order to have the best result. However, these lessons are not what causes welding to take so long to learn, that is due to the repetition necessary to understand the effects of the above factors. That is the portion of the process that can be targeted by a system developed to minimize the number of repetitions necessary in order to manage these factors by feel alone.

4.3 Preliminary Designs

Based on the data that we collected from the interviews with people working in the welding industry, a total of five different designs were created to help transfer tacit knowledge to new welders by reducing the number of repetition welders needed to perform. Although these five designs are merely concepts, each one has been carefully thought out based on the guidelines for system development. After discussing each designs' capability and limitations as a group, they were given a total score using Pugh analysis based on the Piecewise comparison chart of the seven guidelines's total score from table 1.

The first design that we thought of was an Augmented Reality system. The AR system would be capable of displaying live information such as temperature, speed, and angles to the welder while they're welding. The visualization of these different sensors could be placed closely to the welder and manipulated via AR controls to not obstruct the weld. By glancing at the sensor feed, welders can adjust the target variables to an ideal range.

The second design is two devices, a welding helmet with a built-in AR system and a welding glove, as shown in Figure 1. The first device is a specialized welding helmet, with an AR display. The AR system inside the helmet would display a general temperature color gradient on one side of the helmet, and the other side display a temperature color gradient for the things such as the metal's plastic and permanent deformation, yield strength, and melting point. There is a program that the user would have to install on their computer to get material properties for metals they are working with, and they would upload that information to their welding helmet. The name of the metal would be displayed on top of the AR screen after being manually chosen from their downloaded metals. Outside the helmet are four buttons and a USB port for data download/upload. One button would switch between normal vision and thermal vision, the second would start recording a video in front of the welder with a small camera located at the front of the helmet, the third button would turn the temperature gradients on/off, and the fourth button would cycle through the downloaded metals.

The second device is a welding glove that is connected to a sensor that tracks the speed and angle of the welder. The welder can set up a range for speed and angle in the program while the sensor is connected. During use, if the speed/angle go above/below the range, the sensor would send a signal to a device attached to the welding glove, and the device would vibrate. The glove also has some protection pads for the fingers and top of the hand.

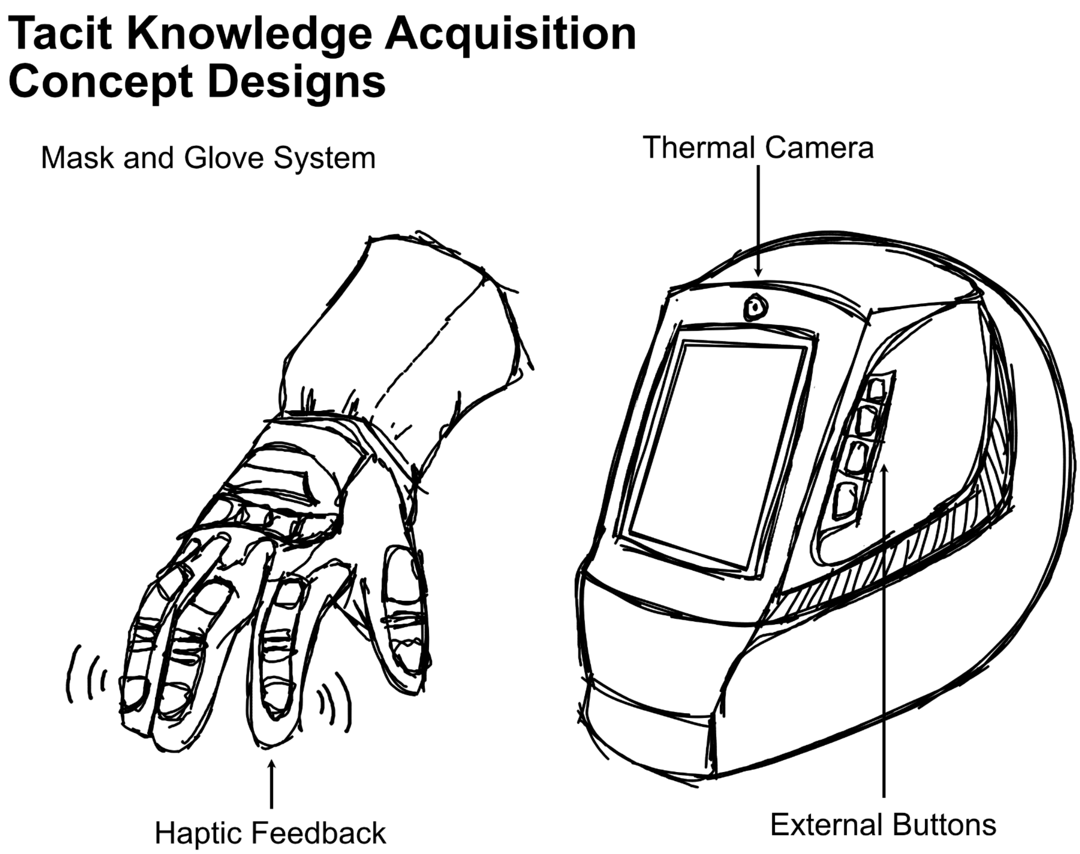

Figure 1: Welding glove and AR welding helmet. The glove is connected to an external sensor that is able to send signals to the glove for haptic feedback. The AR welding helmet has an AR screen, thermal camera in the front, and external buttons on the side.

The third design is an affixed display screen that attaches to the welding torch (Figure 2). The screen would be attached using a bracket and it would display data in real time. There is a gyroscope within the welding screen that displays the angle and position using multiple small leds spread out horizontally. The green bar in the middle would be the ideal angle and position, manually put in by the user, and there is a ball that would move based on the values of a specific variable. The user can change the metal and its thickness on the screen. The device would be incapable of a heat map, but is capable of having a heat sensor. It is also capable of recording a video that can be played back using a software built for the device.

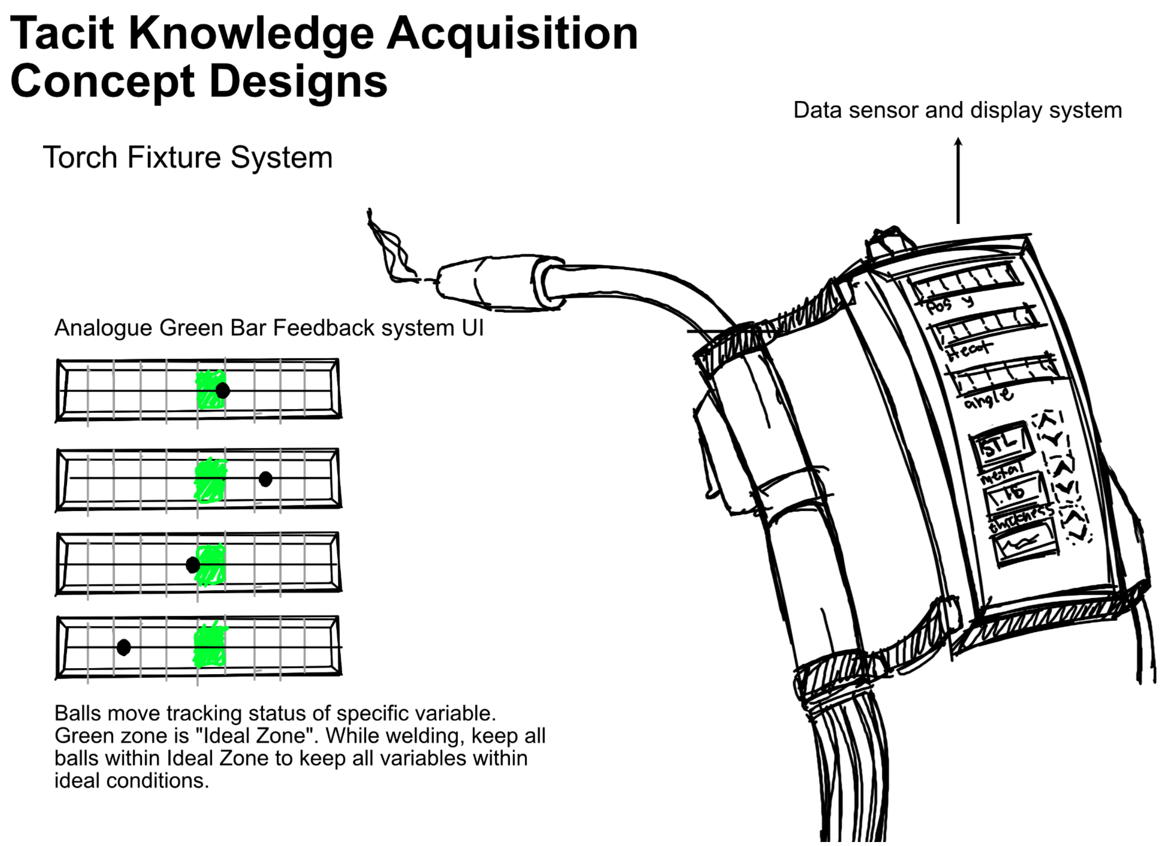

Figure 2: Torch Fixture System attached to a welding torch. There is a sensor in the front that sends data to the bars on the display system. Inside the bar contains a ball that moves based on the values of a specific variable, and an analog green bar for the "ideal zone" of that variable.

The fourth design that we came up with was a sensor software system. The sensor software system is capable of recording a video of a welder welding in conjunction with sensors on the torch to provide information about position, and the ability for welders to watch the video recording of them welding after they finished. There are multiple cameras at different positions, which allows the welders to watch the recording from different angles. The video playback would occur alongside data collection from the torch sensors to provide the welders visual feedback along with the speed and angle of the torch.The program is also capable of changing the display of temperature, speed, and angles to graphs comparing their values to time instead of numerical numbers. The data collected can be easily stored and located, as well as exporting to text-based file programs.

The fifth design, created in an attempt to combine the benefits of all previous designs, is the Internal Mask System (Figure 3). The Internal Mask System is a device that can be used with any previously owned welding mask. The device has three parts: torch mounted sensors, a live feedback display, and an external configurator. The live feedback display, which could easily be affixed to the interior of any welding mask with glue or double sided tape, would have an analog arrow display for important variables such as temperature, speed, and position recorded by the torch-mounted sensors. The arrow would change color based on how closer the welder is to the "ideal" range (red, yellow, or green). The external configurator would allow the user to change settings such as metal type and thickness. The data obtained from the welding duration can be displayed as graphs in a program by exporting it through a USB (Figure 4). The program would then give a score based on the precision and accuracy of the welder based on how close they are to the ideal range.

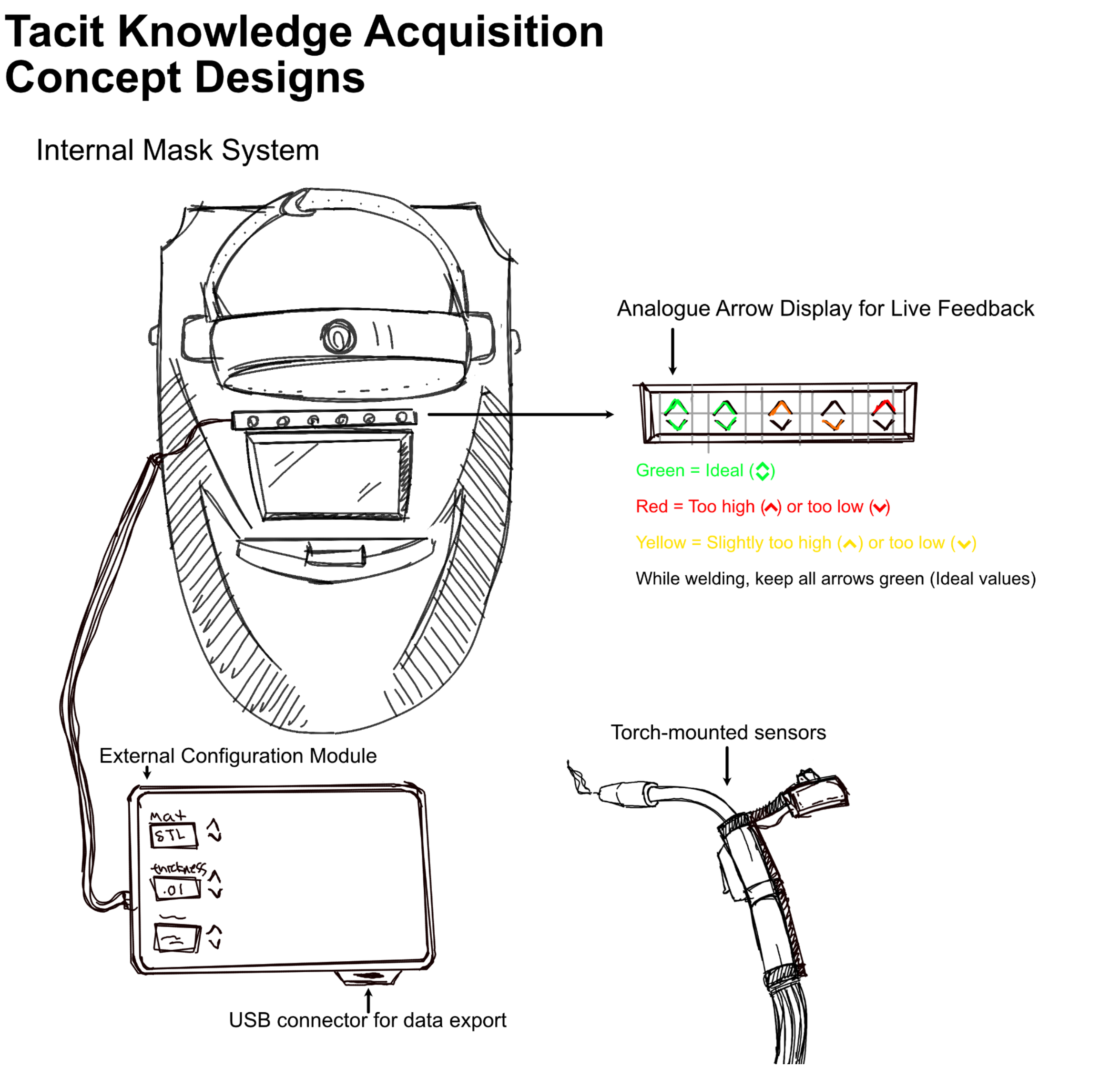

Figure 3: Internal Mask System with an external configuration module and an analog arrow display that can be attached to a welding mask. The torch has a sensor that measures things such as position, temperature, etc.

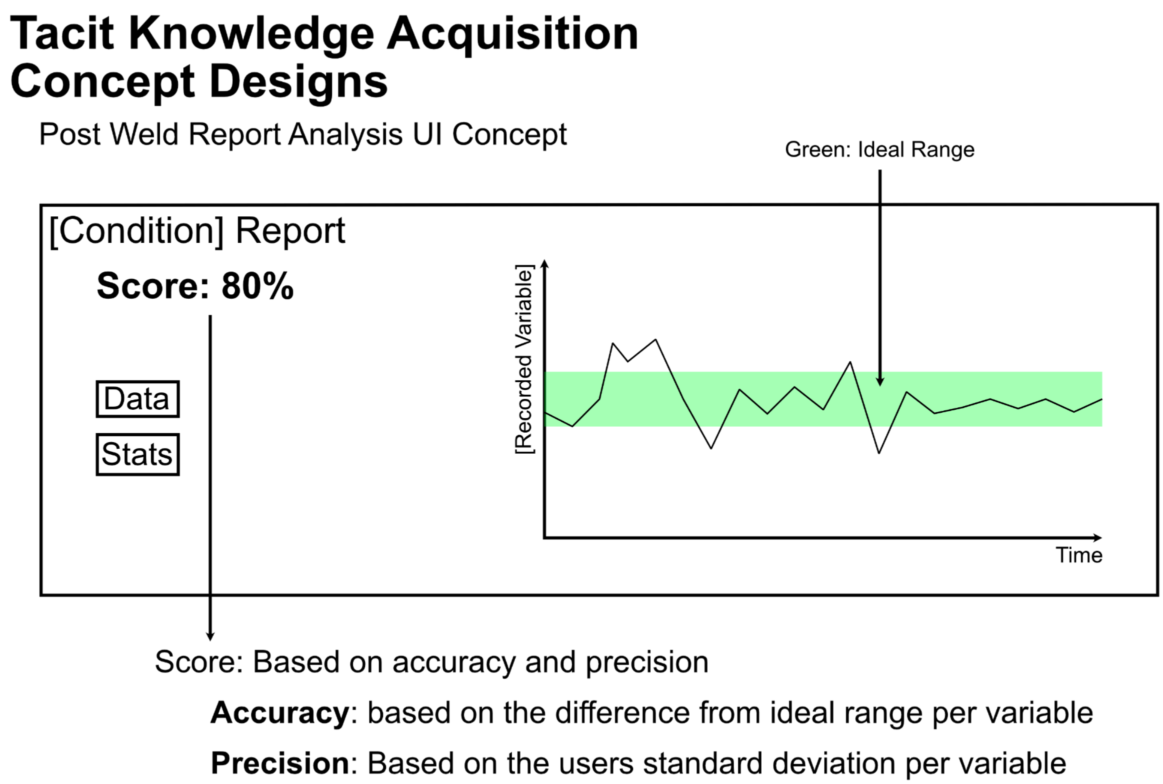

Figure 4: Concept UI for the post-weld report for Internal Mask System Software. A graph for recorded variable vs. time graph based on the data obtained from the sensor is shown. The green bar is the ideal range, and the graph gives a score based on your accuracy and precision.

To conduct the Pugh analysis, each of our designs were compared to the baselines listed in the methods systems. For each baseline statement, the designs were given a score ranging from -2 to 2, relating directly to whether or not the design met, failed to meet, or exceeded the baseline expectation. A score of zero met the baseline, a score of negative two drastically falls short of the baseline, and a score of positive two far exceeds the baseline. A score of one and negative one fall somewhere in between, falling either slightly short or slightly exceeding the baseline respectively.

CATEGORY	WEIGHT	AR SYS	MASK & GLOVE	TORCH FIXTURE	INT. MASK	SENSOR SOFT-WARE
REL	4	0	0	0	0	0
USE	6	0	0	0	0	0
RTF	3	1	1	1	1	-2
UI	2	0	0	-1	0	0
PRAC	5	-1	-2	0	0	0
HQ	1	0	0	0	0	0
CON	0	0	0	0	0	0
TOTAL	–	**-2**	**-7**	**1**	**3**	**-6**

Table 2: Pugh analysis score for each design based on the Piecewise comparison chart.

The goal of this analysis was to determine which of the proposed designs most adequately met our requirements. By comparing these designs to a baseline, we produce an estimate of how close to an ideal system the final design is. The design with the highest ranking will be selected to produce a prototype. Based on the Pugh analysis score of the five different systems, the highest scoring design was the Internal Mask System.

4.4 Design Decision Discussion

The production of five different designs provided a wide range of potential for a system aimed to accelerate the acquisition of tacit knowledge. Each of these designs also sported their own roster of concerns.

While the AR system would theoretically be the most versatile design it had several glaring flaws, key amongst them being cost, fragility, and post work analysis. Current AR technology is extremely expensive with current prices costing up to over $3000 per set of goggles. For a product that is expected to be used as a learning tool rather than a permanent addition to a welder's arsenal, having such a high price is a deterrent to any possible buyers. Another concern was the durability of the goggles. Current AR goggles are only designed to withstand a light bump while within a person's home, not the rough environment of a factory or workshop. Anything from falling debris to stray welding sparks could damage the goggles and in the event of such damage the cost to repair the goggles will be great. Additionally, motion sickness is a reported issue one could have using an AR system, which would be harmful to the learning process and provide discomfort to the user[16]. Due to these glaring issues, including theoretical high cost, low durability, and the possibility of motion sickness from using the headset, the design ranked lowly in the Pugh analysis.

One of the greatest concerns for the initial AR design concept was the fragility of the system, so the Mask and Glove design was conceptualized in order to circumvent this issue with a far more durable design. Originally it was meant to be an overall improvement over the AR system that would not only cost less but would be more durable. Unfortunately this design is notably more impractical in use than the AR system. The mask would have been a custom welding mask that held a built-in computer system that would not only wirelessly connect to the glove but would also display the data onto an integrated heads up display. The technology needed for the mask exists for larger applications but would need to be restructured to fit inside of the mask itself. The technology for the glove already exists at the scale needed, but showcases other concerns. Using a combination of motion sensors and digital gyroscopes the glove was expected to be extremely bulky and would severely hinder the welder's degree of movement. Another issue stemmed from the usage of a haptic feedback system integrated into the glove. The use of vibrations could not only interfere with the students ability to maintain a steady movement but it could also go unnoticed and have no impact at all. After careful discussion, the glove portion of this system was deemed impractical in use, given it was more likely to interfere then help the student learn. The mask, on the other hand, showed promise of further improvement, but the cost of the proposed system severely limited its adaptability. Because of the high cost, issues with maneuverability, and overall impracticality, this design also ranked lowly on the Pugh analysis.

The torch fixture design would have not only been significantly cheaper to produce but it would also be a significant improvement on durability. Utilizing hose clamps to affix itself the torch fixture design would be a much smaller investment of research as much of the current technology needed already exists at the size needed to fit inside of the protective housing. The largest drawback of this design stems from its bulky design and large size in comparison to the torch it would be attached to. The weight alone of the device would interfere with the students ability to move in a straight line while the size of it would act as an obstacle blocking their vision. Another issue was that it would likely prove to be a distraction that would prevent the student from obtaining any tacit knowledge. Being placed directly in the center of the students visibility, the student would feel more inclined to pay attention to the device, relying on the feedback, instead of their weld, likely causing them to make many mistakes. Another issue with the torch fixture design was the visibility of the feedback interface. With the necessity of a protective visor to protect from arc flash, any source of light that needs to get through the film would need to be incredibly bright. Any interface created would not only struggle to be seen but would also degrade extremely quickly due to the intensity of light required. The lack of a user interface that can be easily seen and understood significantly hampered the potential of the torch fixture system, as reflected in the Pugh analysis.

The sensor software system offered an unparalleled level of post work feedback that welding instructors would find essential in helping to identify future improvement for their students. With the ability to record their students' work while also giving an accurate analysis of the weld itself, this would allow a teacher to not only identify the exact moment their student made a mistake but it would show the raw data of what outliers caused the weld to fail. This function allows teachers to provide feedback to their students with a level of detail that is previously unavailable. The underlying flaw with this design is the complete lack of real time feedback to the student. Without any form of immediate feedback for the student, improvements to their welding will only occur post practice. While the lack of real time feedback ultimately hurt this system’s ranking, it was clear that the powerful post-work report was essential for future design iterations.

Though the Internal Mask system ranked the highest in the Pugh analysis and thus was selected for more in-depth designing, it was not without its own concerns. The Internal Mask system functions using a multi-device system that is made up of three separate modules connected by wires. A major concern is that the location of these wires will inhibit the ability for welders to properly maneuver while the system is engaged. Another major concern is the vulnerability of the torch-mounted sensors as they are subjected to high heat for extended periods of time. There is another additional concern regarding the strength of adhesive needed to properly apply the LED display to the inside of the welding mask, as it would be working in an environment of high heat and moisture due to the proximity to the welder's face. Despite these concerns, however, the immediate real-time feedback system and the system's ability to meet the rest of the baselines outranked its competitors.

Because our final design decision relied so heavily on the Pugh analysis, it is worth mentioning that the final design selected was determined almost explicitly by the weights determined via the Piecewise analysis in section 3. After some discussion with the group, we determined that the most important aspects of a successful system were that it would be a practical system that would give relevant, useful information in a timely manner. Should we have decided that the system did not need to be practical, this would have likely changed the kinds of designs brainstormed and their rankings in the Pugh analysis. Or, if we had decided that a different feature was of great importance–such as the ability to play back recorded data to analyze and observe–certain rankings would have shifted and other designs may have received the highest score. Our design decision is influenced entirely by the weights decided in the Piecewise analysis, and the Piecewise analysis determines what aspects of the design are the most important to consider.

4.5 Internal Mask System

The culmination of the design processes is the Internal Mask System, a system designed that could provide all the benefits of previous designs while minimizing the known flaws of these designs. The system was designed in three primary "modules" in order to be efficient and helpful to any welder with any equipment, while also minimizing costs (figure 3).

The first module is a torch mounted sensor assembly, capable of reading all important variables like position, speed and heat. The position and speed sensors would be standard for such measurements, requiring simple calibration before use. To read heat, a light infrared laser would be affixed on the uppermost region of a welding torch. It would also have a standard red-light laser used to calibrate a target location for temperature reading.

The second module is the live feedback display, which could be easily affixed to the interior of any welding mask just above the visor using simple adhesive or tape. Using an analog display with multiple arrows, the system could display the conditions of each important variable efficiently by relying on visual information in order to prevent distracting the student. This display would have two primary systems: arrow direction and arrow color. An upwards pointing arrow would signify that the tracked variable is too high from the ideal range, while a downwards pointing arrow would signify a variable is too low from the ideal range. These arrows would come in two colors: yellow, signifying low to moderate divergence from ideal, and red, signifying a major divergence from ideal. If both the upward and downward arrows are present and green, it would signify that the variable is within ideal range. Each variable would have one arrow assembly track, labeled by a simple light box to be visible in the dark conditions of a welding mask. Using this system, a student could keep track of all measured variables without looking at the display using peripheral vision to keep track of the color and location of the arrows. Additionally, order of the variables could be easily memorized, such that a student would not even have to look up at the display to know which variable has strayed from its ideal range. In short, if the system works as designed it would allow a student to keep track of all important information without ever looking up from their weld. For testing or practice purposes, this display could also be turned off or removed altogether without compromising the systems data recording capabilities in order for a student to test their skills without the aid of the display while retaining the ability to analyze it later with the included software.

The third module is the external configuration module, which is connected to the live feedback display by a long wire and can be easily clipped to a sleeve or belt to stay out of the way when not in use. Using this module, the user can input all necessary information for the weld, such as material and material thickness. Using these input settings, the system would change the ideal ranges for each variable based on either manually recorded data, taken by an instructor prior to giving the system to a student, or via a database. Additionally, this module could be connected to a computer through standard means, such as a USB connection, in order to access software. Using this software, inspired by the Sensor Software System Design, students or instructors could access all recorded data as either raw data or graphs (Figure 4). Additionally, this software could have a variety of different features to aid in the learning process.

The goal for the Internal Mask System is to create a easy to use, flexible and practical system to allow students to gain real time feedback while they weld to streamline the process and decrease the number of repetitions necessary to acquire the tacit knowledge needed to manage important factors necessary to create a good weld by feeling alone. This proposed system would be able to give the student easy to understand feedback without distracting them from the weld and provide many features and post-weld reports to further optimize their learning experience. This system is not designed to replace instructors; it cannot teach the fundamentals of welding, such as the general order of operations, but the goal of this project was not to replace instructors but rather provide an additional tool to increase the rate of tacit knowledge acquisition. This system would work in tandem with an instructor to teach a student as efficiently as possible and provide feedback necessary for growth, quicker than ever before.

Section 5. Conclusion and Recommendations

5.1 Summary

The impact of tacit knowledge on everyday life is substantial, and this type of knowledge is the foundation of countless skills used every day. This knowledge is not gained through studying or read in literature, but instead acquired by countless hours of practice and training. In an effort to understand the acquisition of tacit knowledge as a whole, tacit knowledge in the welding industry was investigated as a case study, with the goal of devising a method through which the acquisition of tacit knowledge can be improved. Due to the precise nature of the work and a declining trend of employment fueling an ever-growing national welder shortage, the welding industry proved to be a perfect choice as a focus for this study. Once the welding industry was chosen as a case study, a questionnaire was created to be used to interview local welders in the Worcester area, in order to understand the complex challenges of the welding industry both in training and the professional workplace. After interviews were conducted our team analyzed our data to search for any trends which were applicable to tacit knowledge. With our findings, we conducted a second round of interviews with additional questions to look further into the prominent trends present in the previous interviews.

The first of these prominent trends was the importance of repetition, which stood out as the most impactful teaching method for welders in training, serving as the main form of improvement for welding students. While academic lessons on the methodology and techniques of welding play an important role in a students journey to becoming proficient in welding, repetition proved to be the fundamental step to perfecting their work. In the pursuit of improving their craft students would need to repeatedly practice a variety of different welds to become proficient. By repeating the same work numerous times, the student ingrains the cause and effect of minute tactile differences within their subconscious. With each mistake, most often pointed out by the instructor through various forms of feedback, the student learns more and slowly begins to understand the “feeling” of a proficient weld. Over time, over countless mistakes, the student gains innate ability to feel when they are diverging away from the optimal conditions during the weld. These conditions are the many factors which produce a “good” weld, which the student learns to manage through repetition.

The second most impactful trend present in the interview results was that a "good" weld is often the product of carefully managing a multitude of factors during any weld. These factors are position, speed, heat, and material qualities. If these inherent factors are mismanaged, the student will likely produce low quality welds. Position describes both the physical positioning of the welding tool and the distance the tool is held above the metal. Speed is simply the pace at which a welder moves across the welding surface, and heat is the result of high energies required during the weld, which heat up the material. These factors, and properly managing them, are necessary for a quality weld. Mismanaged position can result in a crooked, uneven bond between the two pieces of metal, capable of forming points of failure when under load. Mismanaging speed and heat can each affect the depth of the weld, creating weak and brittle welds, either by burning through the metal or creating a weld which does not penetrate deep enough for adequate strength. Finally, the material qualities of the metal, including physical qualities and thickness, affect every step of the weld and dictate how a student must manage the previous factors. The ability to balance these inherent factors subconsciously while noting the feeling of the welding process combines together to form the innate tacit knowledge needed to become proficient in welding.

From the results acquired from these interviews, our team created theoretical designs for devices that would improve and optimize the teaching process of the welding industry, imparting tacit knowledge into students faster and easier than ever before. Through a rigorous design process, our team refined the proposed systems into a single product, the Internal Mask System, designed to target repetition and give students immediate, automated feedback showing students exactly how well they are managing any given variable during the weld, optimizing the training experience of student welders. If the Internal Mask System is successful, it would be able to reduce the training time and improve the employment rate of the welding industry, possibly preventing a future scarcity of welders.

5.2 Limitations

This study is not without limitations. The interview process only included three local interviewees who primarily worked with the industrial, manufacturing and artisanal applications of welding. Our data lacked in-depth research of other welding industries, such as adverse conditional welding, a practice that could offer different requirements compared to industrial or artisan welding. By interviewing only three local welders our data was limited to a very small percentage of the welding industry. With a global presence, the welding industry faces many changes dependent on the region. Different regions of the world could theoretically provide additional factors that would need to be considered for the design of future training systems. Additional factors like humidity and ambient temperature could affect the welding process in unexpected ways. Time also served as a more generalized limitation for our team. With the constraints of an academic calendar our study was limited to seven months. Theoretically, with more time available, more interviews could have been conducted and from those interviews new data could have been discovered that would have influenced our finding and designs in a substantial way.

5.3 Recommendations

First, we recommend that a prototype for the Internal Mask System is developed and its effectiveness tested on student welders. For future iterations of this study several changes are recommended to be made. With time being an overall limiting factor in this study, we recommend reserving a greater duration upon which future studies may be conducted. This increase in time is expected to allow more data to be collected at the interviewing stage. With more interviews conducted, the data collected may provide greater insight into challenges and learning methods of the industry, which would provide additional insight for the applications of tacit knowledge and its acquisition. Additionally it may introduce more factors and conditions which would have to be considered during research. We recommend a wider range of welding professions to be interviewed in future studies. The results of this study was entirely based on the responses of local shops which specialized only in industrial and artisan welding and their challenges within these respective industries. Because of this, the findings of this study are only confirmed to be applicable to a small fraction of the welding industry. Widening the scope of this study, the research conducted might provide greater insight into tacit knowledge as a whole and possibly discovering additional trends that would influence the results of this study. The designs of possible training systems would be altered to accommodate the additional trends discovered. These alterations are expected to broaden the capabilities of the subsequent designs to be capable of teaching a larger variety of welding professions.

5.3 Wider Implications

Given the subconscious nature of tacit knowledge, direct study of the subconscious and physiological phenomena is challenging. Tacit knowledge is in every unconscious action, it influences the movement of writing, the balancing act while riding a bike, and, of course, welding. It serves as the innate physical knowledge each individual accumulates throughout their life resulting in a subconscious “know how” that is the culmination of knowledge built by each past experience. Through experience and practice, a person’s tacit knowledge grows as they subconsciously record and categorize the outcome of their actions. Unlike academic knowledge which can be expanded with conscious effort, tacit knowledge is acquired best with experience, through gradual understanding of cause and effect. Naturally, acquiring tacit knowledge is a time consuming process. Within so many industries worldwide, precise tacit knowledge is required resulting in months to decades long training periods, serving as a bottleneck that prevents these industries from growing and meeting the industry demands. For essential businesses, such as the welding industry used for this study, this training period can be damaging, causing scarcity in an ever growing market. While this study focused on the welding industry, the implications of the proposed Internal Mask System are indicative of tacit knowledge as a whole. It was a system designed to quantify important variables through data and visual display, and by consequence shorten long repetition focused training periods within the welding industry. Additionally, these methods used for the Internal Mask System could be applicable to countless other industries, potentially paving the way to revolutionize these industries which fundamentally rely on tacit knowledge, from visual designers to dentists and beyond. The Internal Mask System could be applied to any industrial field which relies on similar manageable variables which affect the product. The potential of such a system does not stop with similar industries. Other industries, such the arts, could similarly identify their own quantifiable variables or boundaries and a similar system could be developed and applied to the field. Alternatively, the information gathered could be used to teach robotic systems which in turn could reduce the demand for new workers in various industries. In short, while the Internal Mask System was designed for welding, the intent of the design is simple and applicable to countless industries which rely on tacit knowledge, having the potential to reinvigorate these struggling industries and inspire growth unlike anything seen before.

Appendix

Appendix 1a: Welder Questionnaire

Introduction:

The purpose of this study is to analyze tacit knowledge learned by experienced welders. This study intends to take feedback on current instructional methods used to teach new welders and the current rate of tacit knowledge acquisition to more efficiently train new welders and alleviate the pressure of the current welder shortage.

This interview will collect information regarding your history as a welder, your training, and your experience with new hires. Data collected will not include personal or identifiable information and will be destroyed after the IQP project is completed. Participation will take 15-20 minutes of your time.

Participation in this interview is voluntary. You may end your participation at any time, and you may decline to answer any question.

Thank you for your time!

Definitions:

Welding project. A series of welds combining multiple components to fulfill a client's request. Welding projects can involve a series of welding processes and can involve many different individual portions.

Welding process. A specific kind of technique used to weld together two components in a welding project. (e.g. stick welding)

Tacit Knowledge. Tacit knowledge is a "type" of knowledge, skills, and abilities gained through experience that is often difficult to communicate or teach to others. Tacit knowledge can be known as experimental knowledge, and requires extensive teaching or practice. It is often difficult to formalize and to express because it is so embedded in the individual that it seems entirely natural.

Category I: Educational History

1. How long have you been welding for?
2. Briefly describe your training to become a welder.
    a. What kind of formal training did you have?
    b. How long did it take for you to enter the workforce?
3. Where did you struggle the most in learning welding processes during your training?
4. What teaching methods did you find most effective to learn welding processes during your training?

Category II: Workforce Experience

1. Among the welding processes you do on a daily basis, which require the most practice to perform?
2. Among the welding projects you do on a daily basis, which require the most practice to perform?
3. How many colleagues do you have? How often do you get new hires?
4. Which welding processes do new hires struggle with the most when they begin work?
5. To address this, how do you train new hires? How long does it take for new hires to achieve full proficiency?

Appendix 1b: Instructor Questionnaire

Introduction:

The purpose of this study is to analyze tacit knowledge learned by experienced welders. This study intends to take feedback on current instructional methods used to teach new welders and the current rate of tacit knowledge acquisition to more efficiently train new welders and alleviate the pressure of the current welder shortage.

This survey will collect information regarding your experiences as a welding educator, regarding your challenges as well as the challenges of your students. Data collected will not include personal or identifiable information and will be destroyed after the IQP project is completed. Participation will take 15-20 minutes of your time.

Participation in this survey is voluntary. You may end your participation at any time, and you may decline to answer any question.

Thank you for your time!

Definitions:

Welding project. A series of welds combining multiple components to fulfill a client's request. Welding projects can involve a series of welding processes and can involve many different individual portions.

Welding process. A specific kind of technique used to weld together two components in a welding project.

Tacit Knowledge. Tacit knowledge is a "type" of knowledge, skills, and abilities gained through experience that is often difficult to communicate or teach to others. Tacit knowledge can be known as experimental knowledge, and requires extensive teaching or practice. It is often difficult to formalize and to express because it is so embedded in the individual that it seems entirely natural.

Category I: Educational History

1. How long have you been teaching for?
2. How many students are in your classes?
    a. How many students are in the welding program in your school?
    b. How large is the welding program at your school?
3. On average, How many percent of students passed your welding program?

Category II: Educational Experience

1. What type of welding processes do you teach?
2. Of these processes, which processes are the hardest to teach?
    a. What makes these processes so challenging?
3. Do students also struggle learning these processes ?
    a. If not, which processes do students struggle with the most?
4. In your experience, what processes do your students take the longest to become proficient in?
5. In your experience, what processes do your students show proficiency in the fastest?

Appendix 2: Followup Welder Questionnaire

Introduction:

The purpose of this second round of interviews is to dive deeper into the trends found with the responses of the previous interviews. As expected, repetition was the most prominent common thread from the interviewees, and the intent of this interview is to understand how and why repetition is so impactful to learn welding, and tacit knowledge skills as a whole.

This interview will collect information regarding your history as a welder, your training, and your experience with new hires, specifically regarding repetition. Data collected will not include personal or identifiable information and will be destroyed after the IQP project is completed. Participation will take 15-20 minutes of your time.

Participation in this interview is voluntary. You may end your participation at any time, and you may decline to answer any question.

Thank you for your time!

Definitions:

Welding process. A specific kind of technique used to weld together two components in a welding project. (e.g. stick welding)

Tacit Knowledge. Tacit knowledge is a “type” of knowledge, skills, and abilities gained through experience that is often difficult to communicate or teach to others. Tacit knowledge can be known as experimental knowledge, and requires extensive teaching or practice. It is often difficult to formalize and to express because it is so embedded in the individual that it seems entirely natural.

Category I: Repetition

1. To the best of your ability, describe what role repetition had in your training as a welder.
2. How did you modify your technique through each iteration?

   a. How did you know when to change your technique? How did you know when not to?
3. What factors are most important to keep track of while welding?
   a. For example, previous interviewees explained that heat, speed and position matter while welding. Do you agree? Would you add any other important factors to this list?
4. How do you manage the above factors?
5. When practicing welding through repetition, how important is feedback?
   a. What types of feedback is most essential to improve? How was this feedback given to you?

Category II: Proposed Feedback System

1. The purpose of this project is to design a system such that the learning period for welding can be reduced. This first iteration of a system targets repetition, in order to reduce the number of repetitions to learn and increase proficiency. The design of this system as of now is to have visual automated feedback, in order for welders in training can have immediate feedback and alter their technique over far fewer repetitions. This system could have, for example, speed, angle, pressure and heat sensors in order to give a welder live feedback, in an attempt to "quantify" welding to be easier to teach and learn. Do you have any thoughts on this proposed system? Would this be beneficial to welders in training?

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