Deterministic Comparison between Commercial Procurement and Project Design Process

Major Qualifying Project

Submitted to the Faculty of
Worcester Polytechnic Institute

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Abstract

A comparison was made of a decision-based technology commercialization model and a project based case study. The model was derived for use with technology-oriented robotic competition embodied in the Worcester Polytechnic Institute (WPI) Intelligent Ground Vehicle Competition (IGVC) effort. The project researched feasibility and available commercialization methods, followed by careful observation of the actual decision approach the multidisciplinary engineers of WPI's IGVC team utilized to design and construct their vehicle. We found that the commercialization model provided information that allowed discrimination between available alternatives which matched our initial goals of cost, availability, and system performance.

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1 Introduction

The project applies universal method of commercial procurement to an actual ongoing new product development process. Background research was conducted in commercialization models, procurement, decision-making, and technology brokering. Additionally, the Intelligent Ground Vehicle Competition (IGVC) team design and development process was observed and reviewed. Through the analysis of all compiled research and observations, a 'best practice' commercialization model was derived.

The commercialization model consists of two parts: the first outlines the actual informal decision process the IGVC team utilized to make design decisions; the second outlines a formal 'best practice' approach to commercializing technology.

The intelligent ground vehicle developed by the Worcester Polytechnic Institute IGVC team is intended for use in an academic competition sponsored by the U.S. Department of Defense. Technology derived through the competition holds potential for use in many other robotics applications. Recognizing and realizing the opportunity to commercialize technology from the competition requires consideration of each part and subsystem configuration from initial design through production. Thus, the intelligent ground vehicle was selected as a case study to compare with the 'best practice' commercialization model.

The IGVC team was observed in a comprehensive non-intrusive manner to outline their design and decision processes by the authors. This informal decision process was condensed and mapped to a simple model for comparison purposes. Additionally, an actual progress timeline was compiled and compared against the team-delineated timeline.

Because of the complexity of the vehicle, two subsystems were selected for analysis using the commercialization model. The parts and configurations identified by the IGVC team were compared to those identified through the commercialization model. A decision matrix that ranked and weighed multiple factors was developed and utilized to make deterministic decisions regarding the best parts and configurations for commercial analysis.

Utilizing a decision matrix that identified the best parts to meet specifications, two subsystems were identified. A bill of materials was then compiled for each subsystem and aggregated into an operation manual, which was utilized to develop a manufacturing plan.

The resulting selected parts and configuration definitions for each subsystem were compared to the actual selections made by the IGVC team. Substantial improvement from the IGVC team's informal process to the 'best practice' commercialization model was demonstrated.

Quantitative analysis of the two processes showed improvement on cost, delivery, vendor sourcing, and innovation. A procurement and commercialization process is critical to ensuring process control and ability to maintain careful, deliberate decision-making throughout the design and development of a product.

The report details the background and literature research (Section 2), methods (Section 3), and procedures utilized to design and develop the 'best practice' commercialization model and deterministic decision matrix. Additionally, it details the comparison process and derived quantitative improvement (Section 4).

2 Background Research

The background reviews the research conducted regarding 'best practice' approaches to commercializing technology, procurement, decision-making, and technology brokering. The background research provided a foundation for the development of the 'best practice' commercialization model, design of the deterministic decision matrix, and observation of the IGVC team design and development process. The methods and results were derived in accordance with the aggregate of knowledge from the background research.

2.1 Commercialization model

Commercialization refers to the process of applying business methodology to bring a new product, service, or idea to the market for profit. Technology commercialization often focuses on utilizing a concept or prototype from one industry to develop a concept, prototype, and production product in another industry (1). Commercialization of technology is optimal when there is active acquisition of ideas, research, development, cultivation of technology, transfer of technology, and strong need to combine all parts to develop, prototype, and mass market a particular technology or idea (2).

The commercialization model is often augmented through the use of feasibility studies and analysis to test the readiness of a product for market. The feasibility analysis is a process of determining whether or not there is viable reason to bring a product to market or derive and commercialize products from industry. As a result, the feasibility analysis is one of the most effective filters for lowering the risk of potential failure upon entry into the market with a new idea or innovation (3).

2.2 Technology transfer

Technology transfer occurs when knowledge and know-how from one industry or organization are repurposed and utilized within another. "One specific form of technology transfer is the transfer of know-how developed with federal funds (say, at research universities and government labs) to the private sector… with the purpose of commercializing promising technologies" (4).

Within WPI, a technology transfer is also occurring between Point Gray (the supplier of the cameras being utilized by the IGVC entry) and the students from the Robotics and ECE programs to learn the necessary code to properly integrate the camera data with that of the LIDAR and GPS sensor subsystems.

2.3 The technology brokering cycle

The technology brokering cycle is a process of cultivating ideas and recognizing opportunity through the transfer of technology across industries. The cycle is composed of several components which, if followed, should result in more robust, innovative, and cost effective product design.

2.3.1 Idea acquisition

Ideas may be developed from a wealth of resources. The best ideas are typically derived from the capture and acquisition of old ideas applied in new and innovative ways and combinations.

Many new product designs are often derived from old ideas put to new use. The process of utilizing old ideas in new and innovative ways is sometimes known as knowledge brokering. Knowledge brokering is most infamously utilized by firms focused specifically on developing better products in specific industries through the utilization of an extensively developed organizational memory combined with a proven brainstorming process.

An example of a knowledge brokering firm is IDEO. IDEO has compiled an organizational memory which is composed of both people and 'things.' This is to say that, as an employee designs new products, they seek inspiration from other products, ideas, and designs within the organization. Designers and engineers are encouraged to touch, take apart, and study objects to better understand their purpose and possible new uses. This process is further enhanced by the organizational culture. In design firms like IDEO, employees are encouraged through incentives to share ideas, contribute to each others' projects, and suggest improvements. Organizational knowledge and understanding is used to create, study, and review new ideas. This method allows for better idea development through careful analysis of past successes and failures.

Best practice for idea acquisition states that the best ideas are derived from a collective organizational memory of not only what has worked in the past, but what has worked across the breadth of the particular idea or components spectrum. In order for this to work, a massive collection of ideas should be the starting point for any desired product innovation. Many organizations and companies accomplish the collection of ideas both through a lead user process and 'stuff' acquisition (5).

One of the biggest hurdles to the knowledge brokering cycle is the retention and effective development of ideas from initial concept through product prototyping. The retention step is crucial to the development of new and innovative products: if you can't remember a concept or idea, you can't use it. (6)

It has been proven that it is substantially more difficult to retain ideas that are not embedded in tangible objects. Thus, while it is important to keep people in an organization who have a breadth of experience, it is also important to transfer their knowledge into tangible objects to aid retention. Organizational memory is difficult to maintain since it grows and wanes with the addition and loss of employees within the organization (6). Within the WPI IGVC Team, the access to online internet videos and unmanned ground vehicle (UGV) data/reports has allowed them to research some 'best parts' and 'best practices', creating an organizational memory.

2.3.2 Initial idea testing

New ideas, innovations, and designs are great. However, without testing and determining commercial viability and usefulness, they carry little worth and in the most extreme cases, can be detrimental to a company. Knowledge brokering is widely regarded as the best strategy for determining commercialization.

Small-scale prototyping improves probability, eliminates the inherent desire to claim victory for perceived solutions, and fosters a simple and effective drive to solve problems. While prototyping is inherently expensive and often results in failures, it provides an opportunity for learning and initial idea testing. (6).

2.3.3 Design driven innovation

Innovation is often hampered simply because an acceptable alternative is readily available. Although the cost of assimilating an available technology may save time and money, innovative ideas may be quashed in the process. One example of hampered innovation is the Wii. Before the Wii was introduced to the market, Xbox and PlayStation were the wave. The games were more complex and graphic intensive, but required a more complex gaming skill set to play. The Wii eliminated this necessity with the addition of accelerometers in the controllers, a new – exciting and active game system was developed which allowed a more intuitive interactive user experience. Without the need for the complex 'gaming skill', a new market was also opened to an older generation that previously would not play the Xbox and PlayStation style of games.

'Radical Changes' in technology can assist in creating a 'Technology Push" of an innovation. In basic terms, the more we can change the meaning of what something is, the more innovative the approach may be to solving that problem (7).

2.3.4 Team member heterogeneity

Especially important to the success of a project in the early stages of conception is the concept of heterogeneity. The IGVC team members were brought together from a number of disciplines. A multidisciplinary team allowed for a greater wealth of organizational memory from which to draw. "Access to diverse know-how and perspectives, therefore, may help nurture and sustain entrepreneurial activity up to the point where more formal mechanisms are activated" (8).

2.3.5 From prototype to commercial product

The key to Innovation through the idea development and design phase of commercialization is creating diverse solutions; however, it also remains necessary after prototyping too. Innovation must be continued to transfer the technology from prototype to commercially viable product. Several additional steps in the cycle emerge from product and idea commercialization (9).

The team had the ability to act as 'research and development first buyers' from suppliers around the world. Effectively utilizing the procurement process and properly leveraging written proposal requests, we the students have an opportunity to "drive innovation from the demand side … creat[ing] opportunities for companies … to take … leadership in new markets" (10).

Companies that want to remain competitive, especially in a downturned economy, must continually bring new ideas, goods, and services to market. "… 91% of executives across all industries … [stated] increasing their company's capacity for innovation [was] critical to creating future competitive advantage and earning profits" (11).

2.4 Attributes of decision making

Decision making is a deliberate process. In order to make effective, impactful decisions processes must be developed and adhered to.

2.4.1 Definition of the decision

Structuring and adhering to a decision model is critical in the decision making process. Aside from the initial phase where a problem is determined to exist and the need for a solution expressed, the design of a decision model is of equal importance. This step can also be seen as the design phase of the decision making process. This is "where alternatives, configuration criteria and attributes are identified and considered." The final phase is where the actual decision is made. According to Corner, Bauchanan, & Henig, a dynamic approach to decision making is the best model to be utilized (12).

Properly used, a well structured decision model will allow the decision maker to learn "about one (criteria or alternative) from working with the other. In a good structuring process, criteria and alternatives both do and probably should generate each other interactively." It is also stressed that Alternative Focused Thinking (AFT) and Value Focused Thinking (VFT) are continually interacting with each other. Unfortunately when decisions were made by the IGVC team, typically a VFT only decision process was used due to its simplicity, concrete, and explicit nature. This occurs in many decision making processes because AFT requires hard thought and usually requires extensive research since AFT is "subjective, abstract and implicit" (12).

There are two basic categories of decision making: decision making under certainty and decision making under uncertainty. Decision making under certainty is when the probable result is able to be calculated within a certain error margin. At the other end of the spectrum is the complete uncertainty in decision making. In this case the decision is based on the varying degrees of payoff for each alternative decision on some probability distribution. The varying degrees of payoff are accessed as the relative (13).

2.4.2 Decision making algorithms

Often, managers hold an implicit bias toward project tasks and deliverables and fail to focus on the greater objective of delivering an end result which satisfies the project or decision need. In addressing this implicit bias, it is necessary to adhere to strict decision making processes which encourage open thought and careful evaluation of all attributes of each decision for each event.

2.4.3 Estimating decision probability

One of the easiest ways to derive probability of an event is to use prior probabilities of given events. Generally the prior probabilities for given events may be derived from previous or existing information about the possible states of nature. This data can then be transformed into a probability distribution which is able to be readily interpreted and utilized in analyzing an event. It is however important to note that while the expected outcome may be easily derived it is not always the best decision maker (14).

2.4.4 Risk

Risk is a relative property of the decision that must be carefully gauged from both a quantitative and qualitative perspective. There are many factors that play a role in making the 'right decision.' A decision is partly based upon the decision maker's previous knowledge, the context within which the decision is made, and the perceived value of all tradeoffs weighed qualitatively versus quantitatively (14).

2.4.5 Maximum likelihood and expected uncertainty

Risk is essentially the valuation of the likely failure of a decision to succeed for a particular event. However, valuation of risk does not adequately gauge the relative likelihood of success of a particular decision under an expected uncertainty.

The idea behind the concept of likelihood is that good things always happen. Thus, if a decision is to be successful it is important to gauge likelihood. A successful decision will always be made if the decision maker is optimistic and utilized a known probability of nature with the largest probability distribution possible. In the case where uncertainty exists, a likely decision may be reached only upon carefully weighing the payoffs for each alternative (14).

2.4.6 Impact of decision making context

Corner, Bauchanan, & Henig state that feedback and corrective action (modifying the objective) is the best way to not only solve a decision problem but to resolve it completely or at the very least "make problems more able to be solved." This process is known as double-loop learning, which is very similar to the reframing process in organizational behavior (12).

2.5 The procurement cycle

Procurement in its simplest form is the ability to obtain all necessary components of a product that is to be produced from the best possible sources, quality, delivery time, and price.

2.5.1 Prequalification (feasibility)

This is the initial exploratory phase of the procurement cycle. Within this stage you know what the product you wish to produce is. It is at this stage where you define if that product is feasible. Within this definition, one must answer the following questions.

- Is there a market for the item you are creating?
- Can you acquire all the components necessary and within budgetary requirements?
- Does your firm have the capability and knowledge to create or assemble the parts?

2.5.2 Innovation

Once you have answered the above questions, the next objective we set forth is, can you be innovative in the way a part is procured, how it is used, or can you develop something that is wholly new and answers a business need. This is the most crucial stage where time needs to be taken to perform the research necessary into the suppliers, innovation ideas and quality concerns/constraints. Once this phase is passed, it is very hard – and sometimes impossible – to return to.

2.5.3 Design

The design process proceeds once the innovation and supply channel questions are posed and answered to the absolute best of your ability. If you have not spent the time to hammer this section out, go back and do it again. Changes are very hard and costly to implement once design phase is underway.

2.5.4 Feasibility/risk analysis

Once the initial design and appropriate signoffs have occurred, a secondary feasibility analysis and risk assessment should be performed. The feasibility analysis will allow you to go back to design and make necessary changes before parts are ordered. Besides cost constraints this is the last chance to make significant changes in a design and could prove the pivotal point between the success and failure of a design process.

2.5.5 Cost decisions

A last look at the budget, as funding is usually the scarcest resource in a new product design; will be your most prominent decision point as to whether you can continue. Is there room again for innovation? Can you build something in-house that has a lower price point or better quality than something you need to buy? This is the stage where the Bill of Materials (BOM) should be created and kept current. A mistake in this phase can cause budget overruns as well as missing a very important resource. E.g., you've bought the batteries, but do you have the cable and fuses to apply power to the circuit? Do you have those items properly sourced for the best quality at the lowest price available?

2.5.6 Manufacturing

Assembly or product creation is now underway. Once you are in the manufacturing and assembly stage, it is near impossible to start over. A project could be scrapped completely if you get to this stage and the previous stages were not performed with appropriate time and effort.

2.5.7 Monitoring

Monitoring is the simple (or sometimes not so simple) case of tracking a product and how it is brought to the target market. Do any of the steps need to be modified? E.g., do new sources need to be acquired – budget modified – or anything else that could go wrong in the supply chain?

3 Methodology

The strategies and methods utilized to compare the IGVC team design and development process to the commercialization model are outlined below. Methods include analysis, background research, detail of the IGVC team observation process, and comparison processes utilized to derive quantitative results.

3.1 Project objective and need

The project sought to compare a 'best-practice' approach to decision making through a formal commercialization model with the informal design approach. The IGVC team informal design and engineering approach was utilized as a case-study for comparison. The intelligent ground vehicle project was an optimal case study due to the complexity, innovative nature, and high-cost of the vehicle. These factors contributed to providing an opportunity to show the potential for significant impact through 'best practice' approaches to commercialization. Through the comparison of both processes, a quantitative analysis showed a clear benefit to utilizing a formal design, development, and decision-making process.

3.2 Research process

Research was conducted among numerous disciplines and included reviewing articles regarding innovation, observation, decision-making, marketing, pre-commercial procurement (PCP), global procurement, dynamic problem structuring, feasibility analysis, analysis. The research sought to answer the baseline question of whether a formalized universal decision-making model is better than the informal approach employed by many engineers in the development, prototype, and commercialization of a new product.

3.3 Intelligent Ground Vehicle Competition need

The need for the Intelligent Ground Vehicle Competition and minimum performance specification is communicated through the rules document provided by the Competition. In comparison, this document would traditionally be created by the marketing department, as a result of market and customer demands, and submitted to the research and development arm of a design firm.

The customer in the case of the IGVC is the Department of Defense, with the broad requirement of producing an unmanned, autonomous, ground vehicle for troop support. Some of the rules require the use of waypoint analysis, object and line detection, speed – control – size constraints, and to securely carry a twenty pound cinderblock. The intelligent ground vehicle must navigate across a proposed field which includes: traversing grass and avoiding obstacles such as trees, sand pits, barrels, and road cones.

3.4 IGVC team observation process

In order to better understand the process the IGVC team employed in the design, development, and construction of the vehicle, a careful observation process was employed for the documentation of their activities. Team activities were documented in part by monitoring their communication via email. Conversations, decisions, and part orders were of particular interest, and careful consideration was taken to note their time of occurrence and content. Additionally, meetings of the team were regularly attended to ensure that the minutes were accurate representations of the meeting content and could be later used in decision analysis and mapping. All observations were placed on a timeline with careful note of the time and content of the observation. Utilization of a timeline provided for the future analysis of the decisions against the given specifications.

3.4.1 IGVC team composition

The intelligent ground vehicle team was composed of individuals from several different disciplines. The team consisted of students with majors in Mechanical Engineering, Electrical Engineering, Robotics Engineering, Computer Science, and an advisor whose focus is in Robotics Engineering.

3.4.2 Design considerations

Given a strict set of qualifying design specifications, the team was tasked with the design and development of an autonomous ground vehicle (IGV). The specification included, but was not limited to, the following:

- Size: 3' >= Length <=7' | 2' >= Width <= 5' | Height <= 6' (excluding antenna's)
- Mechanical E-stop: 2' >= center rear of vehicle <= 4'
- Wireless E-Stop: effective for a minimum of 50 feet. Wireless E-stop will be held by the Judges.
- Max Speed: must not exceed the maximum speed of five miles per hour.
- Lane Following: The vehicle must demonstrate that it can detect and follow lanes.
- Obstacle Avoidance: The vehicle must demonstrate that it can detect and avoid obstacles.

- Waypoint Navigation: Vehicle must find a path to a single 2 meter navigation waypoint.

In addition to the basic size and safety considerations, the robot also had to perform the following minimum objective, control, and obstacle course specification:

II.1 OBJECTIVE
A fully autonomous unmanned ground robotic vehicle must negotiate around an outdoor obstacle course under a prescribed time while staying within the 5 mph speed limit, and avoiding the obstacles on the track.

Judges will rank the entries that complete the course based on shortest adjusted time taken. In the event that a vehicle does not finish the course, the judges will rank the entry based on longest adjusted distance traveled. Adjusted time and distance are the net scores given by judges after taking penalties, incurred from obstacle collisions, pothole hits, and boundary crossings, into consideration.

II.2 VEHICLE CONTROL
Vehicles must be unmanned and autonomous. They must compete based on their ability to perceive the course environment and avoid obstacles. Vehicles cannot be remotely controlled by a human operator during competition. All computational power, sensing and control equipment must be carried on board the vehicle.

II.3 OBSTACLE COURSE
The course will be laid out on grass, pavement, simulated pavement, or any combination, over an area of approximately 60 to 120 yards long, by 40 to 60 yards wide and be 700 to 800 feet in length. This distance is identified so teams can set their maximum speed to complete the course pending no prior violations resulting in run termination. The course boundaries will be designated by continuous or dashed white and/or yellow lane markers (lines) approximately three inches wide, painted on the ground. Track width will be approximately ten feet wide with a turning radius not less than five feet. Alternating side-to-side dashes will be 15-20 feet long, with 10-15 feet separation.

Expect natural or artificial inclines with gradients not to exceed 15%, sand pit (sand depth 2 - 3 inches) and randomly placed obstacles along the course. The course will become more difficult to navigate autonomously as vehicle progresses. The sand pit may be simulated with a light beige canvas tarp covering the entire width of the track for ten feet.

Obstacles on the course will consist of various colors (white, orange, brown, green, black, etc.) 5-gallon pails, construction drums, cones, pedestals and barricades that are used on roadways and highways. Natural obstacles such as trees or shrubs and manmade obstacles such as light post or street signs could also appear on the course. The placement of the obstacles may be randomized from left, right, and center placements prior to every run.

Potholes will be two feet in diameter and two inches in depth will be placed on the course. Simulated potholes are two feet diameter white circles, and may also be used on the course (Course width will be adjusted here to insure minimum passage width).

There will be a minimum of six feet clearance, minimum passage width, between the line and the obstacles, i.e. if the obstacle is in the middle of the course then on either side of the obstacle will be six feet of driving space. Or if the obstacle is closer to one side of the lane then the other side of the obstacle must have at least six feet of driving space for the vehicles.

Also in the event will be complex barrel arrangements with switchbacks and center islands. These will be adjusted for location between runs. Direction of the obstacle course may also be changed between heats (15).

3.4.3 Data/vehicle parts reviewed

The intelligent ground vehicle consisted of many parts and subsystems to complete the aforementioned required objectives. The parts selected to comprise each subsystem had implications for the overall performance of the vehicle in terms of ruggedness, power consumption, processing power, and more. As a result cost reduction, system performance, and feasibility of commercialization were integrally tied to the parts and subsystem configurations which comprise the vehicle.

The subsystems of the vehicle included the chassis and drive train subsystem, power distribution subsystem, processing subsystem, controller subsystem, and sensor subsystem.

In reviewing all subsystems, it became apparent that each one played a unique role in the vehicle as well as had a system impact. However, two subsystems were identified as able to show more potential for improvement than the others. The cameras, within the sensor subsystem, were selected for review due to their innovative nature, wide array of options available, and potential system performance implications

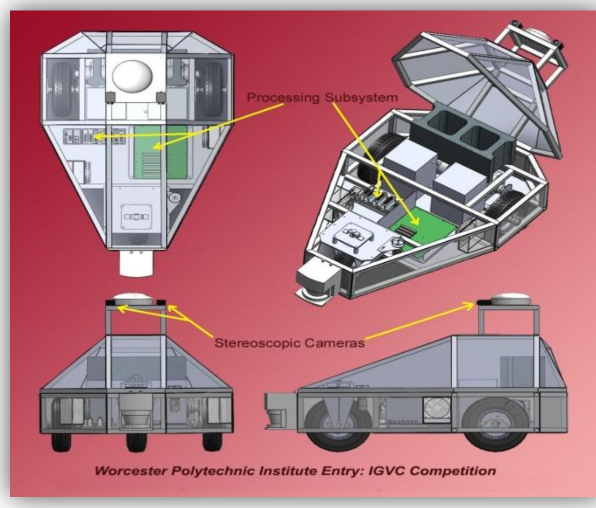

Figure 1 - Chosen Intelligent Ground Vehicle Subsystems

The processing subsystem was also chosen for review. The processing subsystem consists of many components which interact to process all the raw data from the sensor subsystem, which subsequently provides path-finding and mapping for the vehicle. The performance of the processing subsystem directly affects the ability of the vehicle to quickly and accurately navigate a course autonomously.

Reviewing the remaining subsystems it is apparent, that had they also been reviewed cost reduction, system performance, and innovation could have been identified within them. However, the cameras and processing subsystem were believed to hold the greatest potential for improvement to the vehicle.

3.5 Intelligent Ground Vehicle Competition team design process

The IGVC team utilized a fast-paced decision-making process targeted at choosing parts, components, and configurations on a short-run timeline. Figure 2 - Informal Design Process details the decision-making process the IGVC team used. The team started by identifying the given specification from the IGVC (http://www.igvc.org/objective.htm). The team then identified parts they believed to meet or exceed a given specification. Often, part selection resulted from donations, identification of past IGVC design successes, or positive relationships between WPI and particular companies. Some feedback was utilized in the decision-making process, but was often minimal at best with little to no peer review of selections.

Our role in this process early on was to try to push for innovation in idea creation. As the project developed, we took a more passive role and observed how the team made decisions and interacted.

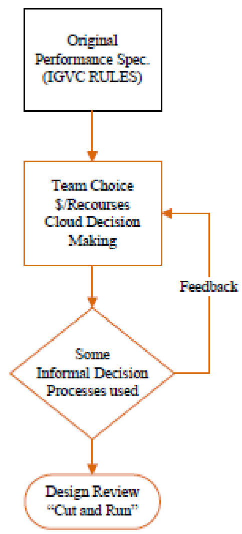

Figure 2 - Informal Design Process

3.6 Commercial model development process

The commercialization model was developed with the intent of creating a decision-making approach that could increase the feasibility of deriving commercial technology from an engineering design competition. The model encompasses two paths. The first path models the process the IGVC team followed for development of their vehicle for competition. The second path models a process by which a specification would ideally result in a viable commercial product.

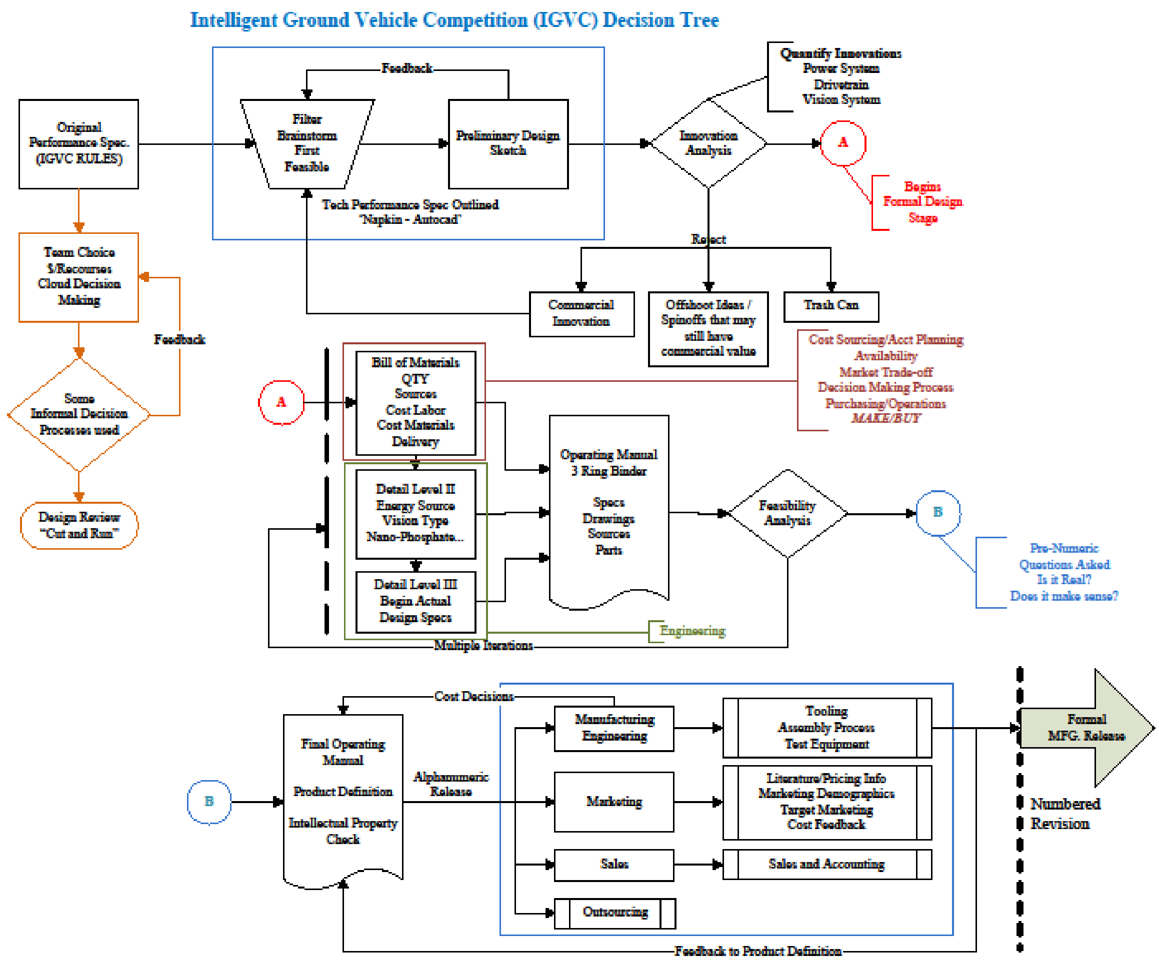

Figure 3 - Complete model showing observed and recommended decisions

The commercialization model is a compilation of several independent models derived and developed to reflect the process from specification, to prototype, to manufacture of a commercial or industrial product. The model was reduced and simplified to include the key decision-making and production aspects of each distinct portion of the commercialization process.

3.6.1 Model design

A model is only effective if it is simple enough to follow and utilize. Development of the commercialization model encompassed the usage of many independently developed models bridged through ingenuity to reflect what exists on a traditional manufacturing floor.

While much of the model was deduced from traditional models derived for the manufacturing setting, innovation was introduced through careful observation of the processes our team utilized in developing the intelligent ground vehicle. With the goal of innovation, driving down cost, decision and procurement time at the boon of the commercial product, it was found that some unique methods were used through the design process. The innovative, lean compilation-based design of the model consists of informal 'bridges' and feedback loops linked together to work cohesively in a decision-making process.

The importance of sketching and vetting ideas in an informal fashion was identified as a necessary step to determine the scope of possibilities for the given specification. A term we coined as 'Napkin – AutoCAD' is used to refer to the initial idea generation or brainstorming often utilized in an informal setting. This phase of informal contemplation of the specification may result in answering questions of scope, innovation, initial feasibility, and potential sourcing. This step often constitutes finding a lead user and/or the initial brainstorming meeting, where ideas may be generated but not necessarily incorporated into the final product. This initial phase can be seen in the snapshot of the model pictured in Figure 4 - "Napkin - AutoCAD"

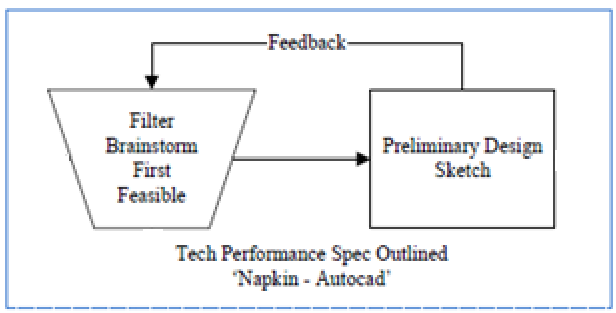

Figure 4 - "Napkin - AutoCAD"

Another innovative design aspect that was embraced as an important piece of the design process is the necessity for an 'off-shoot' ideas category. Keeping a repository of these ideas from the commercial process is important in development of organizational memory, which results in a technology brokering system that is both beneficial to the organization and future product development. The off-shoot design category can be seen in the snapshot of the model pictured in Figure 5 - Offshoot Ideas Repository.

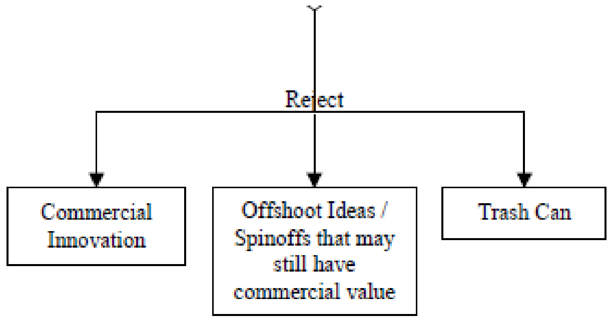

Figure 5 - Offshoot Ideas Repository

Through these two highlighted methods of innovation a clearer picture of the final product is derived. However, methods of standard decision making and design were also identified as an integral piece necessary for the development of a viable commercial product.

3.6.2 "Napkin - AutoCAD"

The decision-making algorithms within the commercialization model focus primarily on validation of ideas generated through feedback loops. There are three key evaluation metrics, with the first one located at the very beginning of the model and focusing on reduction of ideas, the second one located within the portion of the model which focuses on the informal design and evaluation process and the last one located within the formal design and evaluation process.

The first decision metric is the initial 'right-of-passage', intended to focus, refine, and reduce ideas developed that could possibly meet the given specification. At this step, initial broad ideas may be defined and weighed against each other utilizing a simple statistical weighted-average calculation. Each idea may be given a level of importance as applicable to the specification. A series of ideas should be generated and passed on to the next stage, which encompasses the initial compilation and Preliminary Design Sketch for the given specification. This step is pictured in Figure 4 - "Napkin - AutoCAD"

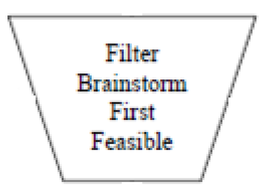

Figure 6 - Idea Funnel

3.6.3 Innovation analysis

Following the development of the Preliminary Design Sketch, a key decision point is reached: the Innovation Analysis. At this stage, ideas are simply evaluated for their potential to both contribute to meeting the given specification and for their potential to substantially improve on any current products that may exist within the commercial or industrial market space. As a result, the innovation analysis is both a research and quantitative driven endeavor. Current market products should be researched and compared to the Preliminary Design Sketch. The innovation analysis is conducted utilizing the decision matrix, as explained in 3.7 Decision matrix development.

Should it be determined that similar products exist, the current Preliminary Design Sketch should be rejected, evaluated for commercial innovation, and returned to the Ideas Funnel (Figure 6 - Idea Funnel) for further review, refinement, and innovative contribution.

It may also be determined that perhaps some aspects of the Preliminary Design Sketch do not contribute to the innovative nature of the end product and should be rejected. Rejected ideas are gathered in a repository and held for later use. Alternately, an idea may also simply be discarded, never to be used again. A snapshot of this portion of the Model is pictured in Figure 7 - Innovation Analysis.

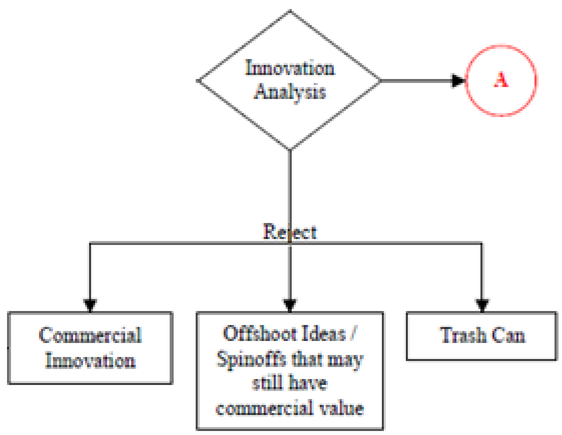

Figure 7 - Innovation Analysis

3.6.4 Bill of materials

After the completion of the innovation analysis, the product moves from the informal design decision-making process to the formal design-decision making process in the model. Each part selected through the idea funnel and innovation analysis is compiled into a bill-of-materials. The bill-of-materials consists of the specification for each part, cost for each part, vendor and sourcing information, and design specification, amongst other details.

After compilation of the bill-of-material for each part, it is then aggregated into a '3 ring binder' of sorts, which is simply the aggregate of all the specifications, drawings, sourcing information, cost information, etcetera. The compilation of the bill-of-materials and operating manual within the model are detailed below in Figure 8 - Bill of Materials.

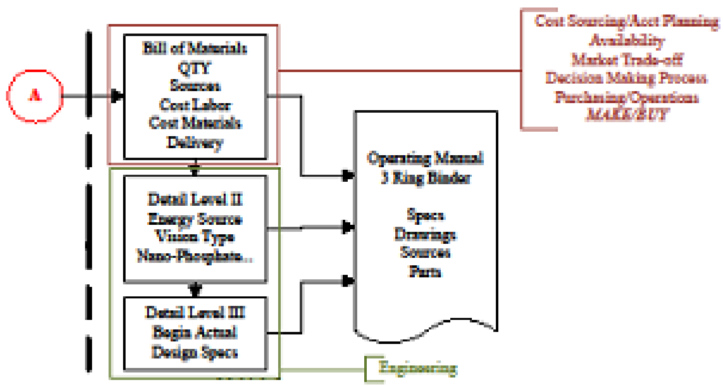

Figure 8 - Bill of Materials

3.6.5 Feasibility analysis

The operating manual provides a level of detail for the product design which is both cost-effective and innovative within the scope of the design specification provided by the competition; however, the commercialization of the product through the model still may not be feasible. So, the final design should be reviewed for market constraints and manufacturing capability, amongst other pertinent questions for the given product. The feasibility analysis may be informal; however, it is important to recognize it as a necessary step to ensure the product design makes sense and can be produced within the given specification.

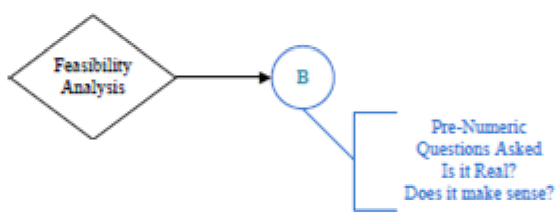

Figure 9 - Feasibility Analysis

The feasibility analysis may result in the product being returned back to either the beginning of the formal design processes or the production of the product may be delayed until it is feasible to produce the product. The feasibility analysis portion of the model is pictured in Figure 9 - Feasibility Analysis.

3.6.6 Final operating manual

After the product has 'cleared' the formal design process portion of the decision model, a final operating manual is developed. The manual details all manufacturing, marketing, sales, and outsourcing requirements. This final stage of the decision model is intended to provide an effective definition of a plan for manufacture of the product before formal release to manufacturing. This final stage of the commercialization model is detailed in Figure 10 - Manufacturing Plan.

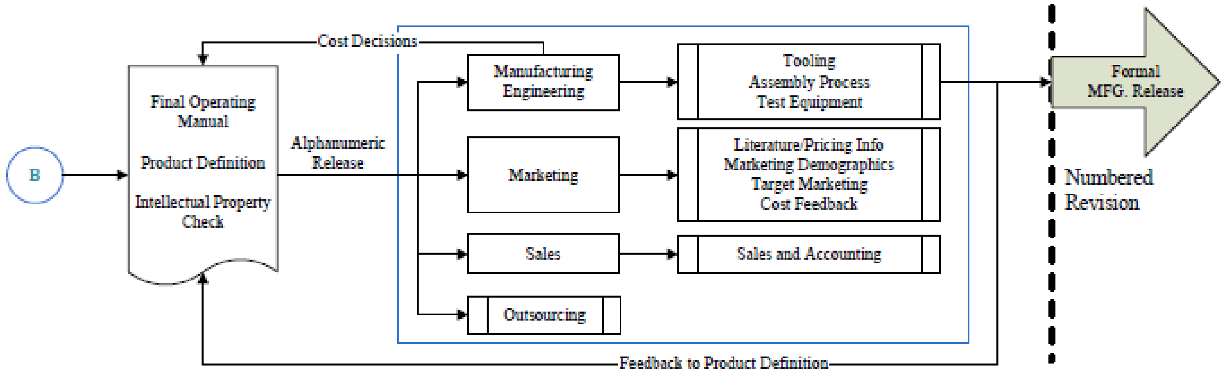

Figure 10 - Manufacturing Plan

3.6.7 Model constraints

While the model conforms to the best practices as outlined by research of the manufacturing setting, consultation with knowledgeable academics, and observed procedures tweaked through the usage of the model, constraining factors still limit the usability of it in the commercial space.

The model is designed to rapidly result in usable decisions and data to drive the design of a product; however, the daunting nature of the various parts and procedures the model outlines may discourage wide usage of the model in its entirety. While utilizing one aspect of the model may improve the commercial development process, as a substantial body of research indicates, incomplete realization of all aspects of the model cannot guarantee great results.

Additionally, much of the initial idea funneling and innovation analysis is based on simple inferences regarding current products on the market (if there are any) and the impact they may have to bring the desired product to market. Thus, bias is easily introduced and able to shape the final design specification and product production. It becomes apparent that a strong project leader must be consulted to ensure that junk data is not used to derive result through the model.

Finally, engineers often become comfortable with a particular company or product line. The result is not only a bias that may be difficult to overcome, but also a tendency to design to the part, rather than design the part for the product. Innovation is stymied and opportunities are missed as a result.

Knowledge of these specific constraints and the opportunity for bias are important to ensure the success of a commercial product within a specific marketplace.

3.7 Decision matrix development

The commercialization model provides a path to follow for the development of a prototype which can ultimately be commercialized. However, while the commercialization model provides an avenue to select a series of subsystem configurations to meet the given specification, it doesn't provide a means for absolute determination of the ideal configuration. As a result, a decision matrix was derived to accomplish this task.

3.7.1 Design of the decision matrix

The decision matrix consists of two parts. The first part is divided into four sets of questions which target: delivery, vendors, cost, and system impact. Each category consists of a series of questions designed to be answerable as either 'yes' or 'no.' Questions that are answerable as either 'yes' or 'no' attempt to ensure that all decisions made through the matrix are of equal importance and effectively target the areas of influence sought through the process. All questions are equally weighted across all categories on the first part of the matrix which provides for the opportunity to review subsystem performance by category. A portion of the first part of the decision matrix questionnaire is exemplified in Figure 11 - Decision Questionnaire.

Technology Commercialization
System Decision Matrix

		Original Specification (cRIO, Consumer Computer, Tesla)	Alternative 1 (cRIO Only)	Alternative 2 (cRIO, Embedded PC, Tesla)	Alternative 3 (Embedded PC, Tesla)	.	.
Delivery							
1	The system can be delivered within the allotted timeframe?	1	1	1	1		
2	The system doesn't require sourcing from multiple vendors?		1				
3	Delivery cost is the vendors?						
4	Delivery is guaranteed within your time window?	1	1	1	1		
5	Does the vendor have a proven performance record		1	1	1		
6	Are there additional benefits?		1		1		
	Total	0.2	0.5	0.3	0.4	0	0

Figure 11 - Decision Questionnaire

The second part of the matrix (decision grid) takes the information from the first part and differentiates each category with a specific 'value rank.' For instance, in a particular project, cost may be a more important factor in the decision-making process than vendor sourcing. Therefore, the questions targeting cost would be weighted more heavily against the questions targeting vendor sourcing. As a result, when the data floods into the decision grid each row represents the 'best option' solution for that particular part or subsystem. The data is then summed and the result is an overall 'best option' selection for the particular part of subsystem analyzed. An example of the decision grid is exemplified in Figure 12 - Decision Grid.

Value Rank	Item	Value Rank	Option 1	Option 2	Option 3	Option 4
1 through 8	Cost	40%	0.16	0.2	0.2	0.32
1 through 5	Vendors	15%	0.06	0.03	0.075	0.075
1 through 4	Delivery	15%	0.03	0.075	0.045	0.06
1 through 9	System Impact	30%	0.03	0.24	0.15	0.27
		Best Option:	0.28	0.545	0.47	0.725

Figure 12 - Decision Grid

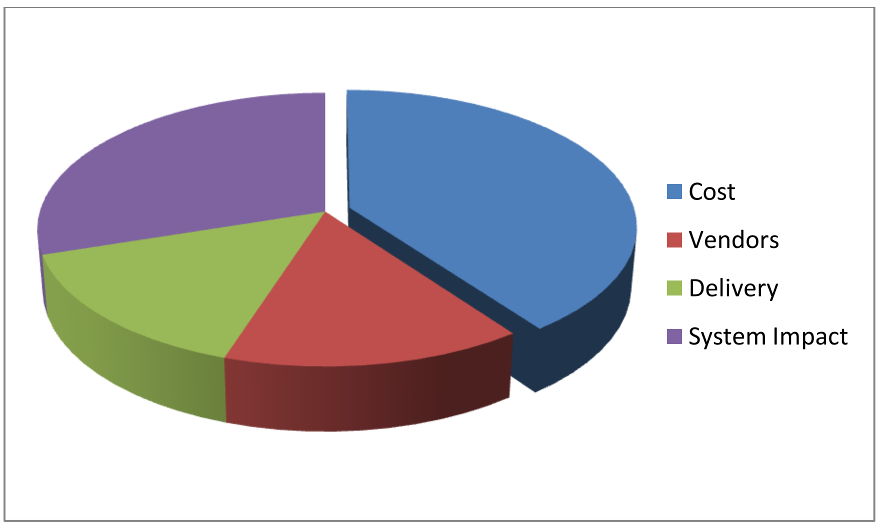

Figure 13 - Weighting

The result of the two part decision matrix is the determination of a 'best choice' decision for the given options. Each decision derived is designed to be 'ideal' based on assigned weight within the 'value rank'. This weighting allows adjustment for importance to be allocated to different categories for discrimination between options. However, at times, one option may be chosen over another despite the decision matrix should the rest of the commercialization model justify and warrant it. The decision matrix 'value rank' allocation may be reviewed in the pie chart in Figure 13 - Weighting

3.7.2 Constraints of the decision matrix

While the decision matrix attempts to address the concerns of favoritism toward various parts and configurations, it too has constraints. One of the largest shortcomings of the decision matrix is that it fails to take into account extraneous factors. One part may present as a better option than another through the decision matrix, but perhaps because of time-constraints, costing options, etc. it may be more effective to utilize a part with a lower rank. However, because the decision matrix is only one component of the commercialization model, such constraints may effectively be addressed later within the model.

3.8 Model comparison process

It is apparent that purpose-driven decision-making through a model may yield better results than an informal process; it still remains necessary to compare both processes to effectively prove this concept. It was detailed earlier that two subsystems were reviewed independently of the team decisions for parts that may have more effectively met the given specification and innovation requirements. Thus, the specific parts that were identified through the model were compared to the parts the team selected for use in the IGVC. Comparison primarily was accomplished through quantitative means in order to derive a specific percentage of improvement, specifically regarding the cost category.

4 Results

4.1 Overview of vehicle

The intelligent ground vehicle consists of several subsystems working together to form a complete system designed to process data, optimize the path, and drive the vehicle down that path. Looking at the vehicle in component format, it becomes evident that each subsystem can be analyzed to determine their viability in a commercial system. As a result of this outlook, it is apparent that a subsystems design is heavily dependent on the specification for the vehicle derived from its desired use. Therefore, a vehicle designed for a military application may require more robust processing capability versus a vehicle designed for the commercial space which may simply require rudimentary processing capability. The following analysis is a product of the assumption that the specification conveyed is appropriate for the application the vehicle is designed for. However, working within the specification there are many readily available options which result in a best solution for the vehicle and potential off-shoot technologies derived from the intelligent ground vehicle.

4.2 Commercial model decision evaluation modeling

From derivation of the specification to the production of a final commercialization strategy for the intelligent ground vehicle, the commercialization model developed and explained in the Methodology was utilized. With emphasis placed on subsystem configuration decisions derived from design specifications and data, rather than engineer's preferences, the results outlined below are believed to be 'best option' selections.

While it would have been ideal to review each subsystem within the intelligent ground vehicle for 'best option' part selection and configuration, two subsystems were chosen because they represent important subsystems. The camera and processing subsystems were chosen for review. The camera subsystem was chosen for two primary reasons. First, the stereovision camera system is one of the more innovative pieces of the intelligent ground vehicle, leaving a substantial amount of room for definition of the specification and decisions regarding what parts meet it. Second, there was a wealth of data available cameras which allowed for determination of the effectiveness of the model utilizing large amounts of data. The second system that was chosen was the processing subsystem. This subsystem was chosen in part because there were a number of possible configuration options available to meet the given specification. The processing subsystem is also a critical piece within the robot and has the potential to have tremendous system impact.

With two subsystems selected, each was carefully evaluated against the commercialization model to determine which part configurations best matched the desired performance specification for the vehicle.

4.2.1 IGVC subsystem analysis through the commercialization model

The commercialization model consists of three primary sections, the informal design process, formal design process, and operating manual plan for release to manufacturing. The three stages of the model are then broken down into specific decision-making gates and loops to ensure each option is carefully vetted for potential inclusion in the final plan for release to manufacture.

4.2.1.1 "Napkin - AutoCAD"

The first portion of the model required initial review of the given specification and identification of what the critical requirements of the project were.

The specification was reviewed to determine the caliber of camera needed to fulfill the design requirement. In talking with the IGVC team, a requirement for a camera of at least 15 FPS at .7 megapixel resolution was identified as adequate to produce a disparity map to accurately and effectively help the robot interpret the world. However, when taking into account the other sensors the vehicle has onboard, some doubt was raised regarding the required precision level of the camera. If other sensors were utilized for object detection and interpretation (aka, the laser rangefinder sensor), then the stereovision camera set could be dedicated to the purpose of line detection and avoidance, according to the IGVC team. Thus, eliminating the need for a color camera and reducing component cost and engineering hours. In turn, the reduction in precision may also have resulted in reduced dependence on the processing subsystem to handle and interpret the image data from the cameras.

From this simple example, it is apparent that careful consideration and review of the specification and desired design is imperative in the build process of any project.

The specification was also reviewed to determine the processing requirements and configuration for the vehicle. However, the majority of requirements for the processing subsystem were derived from the identification of resources requiring processing power, such as the cameras, lidar[1], global positioning sensor, motor encoders, motors, etc. As a result, the processing subsystem configuration could take on many forms. Several configuration options were subsequently identified

[1] **LIDAR** (**Li**ght **D**etection **and** **R**anging) is an optical remote sensing technology that measures properties of scattered light to find range and/or other information of a distant target (17).

with components from a wide range of manufacturers chosen for each configuration option. All the options may be reviewed in Appendix D – Processing . At this stage, the parts were reviewed and parts for each configuration option were chosen. The parts selected for each configuration option were selected by reviewing which parts fit each configuration option best and what their cost-impact on the particular configuration option was.

Contrary to the camera selection above, which was used to demonstrate the effectiveness of the commercialization model on a part level, the processing subsystem analysis was utilized to demonstrate the effectiveness of the commercialization model on a subsystem level.

4.2.1.2 Innovation analysis and decision matrix

After careful review and development of a list of parts and subsystem configurations that could possibly meet the given specification, all the configurations were evaluated through the innovation analysis. The innovation analysis is accomplished through the decision matrix. Through the decision matrix specific parts and configurations were chosen to be incorporated into the bill of materials for the intelligent ground vehicle. Both the camera and processing subsystem configurations were analyzed independently through the innovation analysis to choose a 'best option' for each subsystem.

Sensor subsystem

The sensor subsystem consists of a variety of individual sensors that give the robot an integrated 'view' of the world. Sensors on the vehicle include: lidar, stereovision, motor encoders, and GPS to name a few of the more impactful ones. The lidar unit is responsible for object detection. The data from the lidar is fed from the sensor to the cRIO unit where it is combined with the inputs from the camera subsystem and then passed to the onboard computer for use in path determination. The stereovision cameras are primarily utilized in line detection and depth of field used for object detection. The data path from the stereovision cameras is similar to the lidar; however image data is processed on the nVidia GPGPU and then passed back to the onboard computer for use in path finding and navigation. The motor encoders are simple quadrature sensors used to determine speed and distance traveled in a given period of time. Lastly, the GPS is used almost exclusively for waypoint navigation.

With thousands of options available that could potentially meet the requirement for line-finding, the stereovision cameras were chosen for analysis. The field of cameras available for use was quickly narrowed down to include several hundred models which potentially met the specification provided for the vehicle. The cameras available which could potentially meet the specifications set forth for the vehicle can be found in Appendix A. From this list, six of the most suitable cameras were chosen for analysis through the decision matrix. The initial questionnaire-style weighting system can be reviewed in Figure 14 - Camera subsystem questionnaire. Each category contains a series of ‘yes’/’no’ questions, which target the specific ideal traits for each subcategory of the questionnaire. After all the questions are answered, each subcategory of the questionnaire displays the ‘best option’ selection if the decision were to be solely based on that category. This allows for detailed analysis of why a particular configuration selection was identified as the best

Technology Commercialization
System Decision Matrix

Prices determined within commercial space of 103 cameras within reasonable spec. with ~ 22% Discount

		1. Original Spec. Flea 2	2. Same Price Higher Resolution	3. Lower Price Same Resolution	4. Lower Price Higher FPS	5. Lower Price Lower Resolution	6. Higher Price Higher Resolution
Delivery							
1	The system can be delivered within the allotted timeframe?	1	1	1		1	1
2	The system doesn't require sourcing from multiple vendors?						
3	Delivery cost is the vendors?					1	1
4	Delivery is guaranteed within your time window?	1	1	1			1
5	Does the vendor have a proven performance record	1	1	1		1	1
6	Are there additional benefits?	1	1	1			
	Total	0.4	0.4	0.4	0	0.3	0.4
Vendors							
1	Are there multiple vendors					1	1
2	Do the vendors provide competitive pricing	1	1	1		1	1
3	Do the vendors provide quantity discounts?	1	1	1		1	1
4	Are the vendors located in multiple geographic regions?					1	1
5	The vendors may custom manufacture parts?					1	1
	Total	0.2	0.2	0.2	0	0.5	0.5
Cost							
1	Is there sufficient ROI for the subsystem?	1	1	1		1	1
2	Have the lowest cost parts been selected for the subsystem?			1		1	
3	Is the subsystem simplified?						
4	Is the subsystem cost effective?						
5	Party quantity discounts may be negotiated?	1	1	1		1	1
6	Is the cost of additonal software included in cost?					1	1
7	Are required accessories inlcuded in cost?					1	1
8	Can the subsystem manufactured within budget?	1	1	1		1	1
	Total	0.3	0.3	0.4	0	0.6	0.5
Total System Impact							
1	The subsystem has a total system impact?	1	1	1		1	1
2	The subsystem increases performance of the total system?	1	1	1		1	1
3	The subsystem minimizes costs within the total system?			1		1	
4	The subsystem reduces parts needed elsewhere in the total system?					1	1
5	The component interactions within the subsystem are simplified?						
6	The subsystem requires minimal additional engineering to work with the total system?						
7	The subsystem uses power efficienty?	1	1	1		1	1
8	The subsystem minimizes weight?	1	1	1		1	1
9	Additional accessory parts available from vendor?					1	1
	Total	0.4	0.4	0.5	0	0.7	0.6
	Grant Total:	1.3	1.3	1.5	0	2.1	2

Figure 14 - Camera subsystem questionnaire

The non-weighted results from each subsection of the questionnaire were then compiled and weighted according to importance in the decision-process in the decision grid pictured below in Figure 15 - Camera subsystem decision grid. The 'value rank' chosen for each category was decided upon based on which factors were most important in choosing parts and subsystem configurations for the Intelligent Ground Vehicle. With that said, these numbers are designed to be variable in order to adjust the decision grid to meet the requirements of other projects.

Value Rank	Item	Value Rank	Option 1	Option 2	Option 3	Option 4	Option 5	Option 6
1 through 8	**Cost**	40%	0.12	0.12	0.16	0	0.24	0.2
1 through 5	**Vendors**	15%	0.03	0.03	0.03	0	0.075	0.075
1 through 4	**Delivery**	15%	0.06	0.06	0.06	0	0.045	0.06
1 through 9	**System Impact**	30%	0.12	0.12	0.15	0	0.21	0.18
		Best Option:	0.33	0.33	0.4	0	0.57	0.515

1 Point Grey, Flea 2, FL2-08S2C, 103:
2 Point Grey, Dragonfly2, DR2-13S2C, 1296 x 964; 20FPS, $596
3 Point Grey, Dragonfly2, DR2-HICOL, 1032 x 776, 30FPS, $620
4 N/A
5 Scion, CFW-1-12C, 1024 x 768, 15FPS, $556.00
6 Basler, Scout scA1000-30fm, 1034 x 779, 30FPS, $747.20

Figure 15 - Camera subsystem decision grid

From the decision grid pictured in Figure 15 - Camera subsystem decision grid, there are two options that prove to be suitable within the given decision weights; however, option 5 proves to be the best choice for the project.

Processing subsystem

The processing subsystem also includes many individual parts which cooperatively work together to gather all sensor data, make path finding decisions, and output those decisions to the motors to move the vehicle in accordance with those decisions. Subsequently, analysis of the processing subsystem provided the opportunity to evaluate the impact decisions have on the total system performance. The processing system could take many forms, from a simplistic single-board embedded computing system to a distributed processing system. However, ultimately no matter what the configuration of the subsystem is, it serves the same purpose. Thus, rather than evaluating the individual parts of the processing subsystem, several configuration options were evaluated to determine which would best meet the needs of the intelligent ground vehicle.

Providing for the wide array of camera choices available and the various alternative component choices that could have been made, initial analysis quickly rose to debate over the need for the substantial amount of processing power initially interred in the vehicle. As a result, analysis was conducted in regards to the initial component choice chosen by the IGVC team to meet the vehicle specification as well as several other alternatives that may have better met the specification and simplified the vehicle.

Upon delineation of the specification provided for the processing subsystem, the original IGVC team hardware configuration was listed along with three alternative hardware configurations that may also meet the specification and performance requirements of the vehicle. The four options included one that utilized the cRIO controller, onboard computer, and nVidia GPGPU; one that utilized only the cRIO; one that utilized the cRIO, an industrial embedded computing system (PC104) and the nVidia GPGPU; and one that utilized the cRIO and an industrial computer. All four of these options and their system impacts can be reviewed in Appendix C – Processing subsystem configuration options.

After identifying several alternative hardware configurations that met the specification, parts were sourced and selected for use within each hardware configuration. The part sourcing information can be found in the Appendix . Once parts were selected for each configuration option, the decision matrix was utilized to choose the best configuration option for the given specification. The questionnaire in Figure 16 - Processing subsystem questionnaire consisted of similar 'yes'/'no' questions to the camera subsystem questionnaire, and was answered in similar fashion. The data from the questionnaire flooded into a decision grid, which allowed for the identification of a 'best-choice' option for the processing subsystem configuration.

Technology Commercialization
System Decision Matrix

		Original Specification (cRIO, Consumer Computer, Tesla)	Alternative 1 (cRIO Only)	Alternative 2 (cRIO, Embedded PC, Tesla)	Alternative 3 (Embedded PC, Tesla)	.	.
Delivery							
1	The system can be delivered within the allotted timeframe?	1	1	1	1		
2	The system doesn't require sourcing from multiple vendors?		1				
3	Delivery cost is the vendors?						
4	Delivery is guaranteed within your time window?	1	1	1	1		
5	Does the vendor have a proven performance record		1	1	1		
6	Are there additional benefits?		1		1		
	Total	0.2	0.5	0.3	0.4	0	0
Vendors							
1	Are there multiple vendors	1		1	1		
2	Do the vendors provide competitive pricing	1	1	1	1		
3	Do the vendors provide quantity discounts?			1	1		
4	Are the vendors located in multiple geographic regions?	1	1	1	1		
5	The vendors may custom manufacture parts?	1		1	1		
	Total	0.4	0.2	0.5	0.5	0	0
Cost							
1	Is there sufficient ROI for the subsystem?	1	1	1	1		
2	Have the lowest cost parts been selected for the subsystem?				1		
3	Is the subsystem simplified?		1		1		
4	Is the subsystem cost effective?		1	1	1		
5	Part quantity discounts may be negotiated?	1			1		
6	Can the subsystem be manufactured in modular format?	1	1	1	1		
7	Can the subsystem be manufactured at a competitive price?	1		1	1		
8	Can the subsystem manufactured within budget?		1	1	1		
	Total	0.4	0.5	0.5	0.8	0	0
Total System Impact							
1	The subsystem has a total system impact?	1	1	1	1		
2	The subsystem increases performance of the total system?		1	1	1		
3	The subsystem minimizes costs within the total system?		1		1		
4	The subsystem reduces parts needed elsewhere in the total system?		1	1	1		
5	The component interactions within the subsystem are simplified?		1		1		
6	The subsystem requires minimal additional engineering to work with the total system?			1	1		
7	The subsystem uses power efficienty?		1		1		
8	The subsystem minimizes weight?		1		1		
9	The subsystem is small form factor?		1	1	1		
	Total	0.1	0.8	0.5	0.9	0	0
	Grant Total:	1.1	2	1.8	2.6	0	0

Figure 16 - Processing subsystem questionnaire

The results of the decision grid for the processing subsystem can be reviewed in Figure 17 - Processing subsystem decision grid. The decision grid is color coded to quickly point out 'best options.' 'Value ranks' are applied to each of four general areas including: cost, vendors, delivery, and system impact. For each of the desired decisions, the matrix quickly discriminates the given parts to show a 'best option' configuration. For the processing subsystem, an embedded PC coupled with a Tesla GPGPU system was chosen by the matrix. This option allows for adequate processing power to handle the high-resolution cameras for path finding, while remaining conscious of power consumption, weight, sourcing, cost, and delivery.

Value Rank	Item	Value Rank	Original Specification (cRIO, Consumer Computer, Tesla)	Alternative 1 (cRIO Only)	Alternative 2 (cRIO, Embedded PC, Tesla)	Alternative 3 (Embedded PC, Tesla)		
1 through 8	Cost	40%	0.16	0.2	0.2	0.32	0	0
1 through 5	Vendors	15%	0.06	0.03	0.075	0.075	0	0
1 through 4	Delivery	15%	0.03	0.075	0.045	0.06	0	0
1 through 9	System Impact	30%	0.03	0.24	0.15	0.27	0	0
		Best Option:	0.28	0.545	0.47	0.725	0	0

Figure 17 - Processing subsystem decision grid

While the decision matrix is a great tool for narrowing down numerous possibilities and determining the 'best option' against a particular specification it is still unable to take into account 'soft' factors which may influence a particular choice. Required engineering hours, customer demands, etcetera are factors that may play into which components are chosen for a project. In the case of the intelligent ground vehicle and the particular processing subsystem configuration options presented, the best option given slightly modified specifications and decision-requirements would be the cRIO embedded computer solution. However, due to cost, limited sourcing ability, and the substantial amount of processing power required, this option quickly moved to the bottom for a more generic option within the decision matrix.

As a result of these factors, the decision matrix is only one of many pieces within the commercialization model. The alternatives identified through the decision matrix may simply be placed aside for use in later projects or may be utilized in different iterations of the intelligent ground vehicle design depending on the particular commercial use it is being designed for. The repository for these rejected ideas is identified under the innovation analysis step within the model, as pictured below in Figure 18 - Rejected configurations.

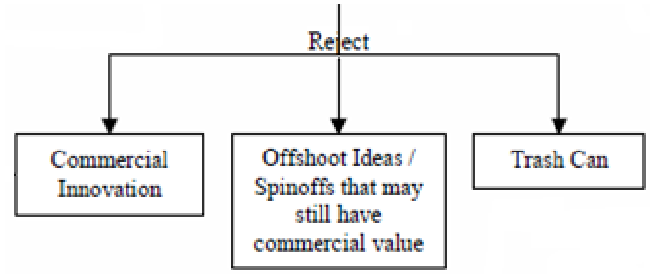

Figure 18 - Rejected configurations

4.2.1.3 Bill of materials development

The bill of materials compilation is the next step within the commercialization model. After suitable part configurations have been selected through the innovation analysis the details for each part and how they fit into the design and development of the intelligent ground vehicle must be compiled.

The bill of materials was not compiled for all of the specific configurations identified through the decision matrix; however, a bill of materials was compiled in cooperation with the IGVC team for the configuration options they selected. The result is an accurate 'real-world' example of a particular bill of materials, if the commercialization model were followed.

The bill of materials provided the IGVC team with an accurate reflection of all the parts that comprise the vehicle and the cost associated with them. The bill of materials, which was developed in accordance with the model for the intelligent ground vehicle, could be analyzed for feasibility of production and utilized to compile a final manufacturing and assembly plan for commercial deployment of the vehicle.

The complete bill of materials for the intelligent ground vehicle may be reviewed in Appendix F – Bill of materials.

4.2.1.4 Final operating manual

The final step of the commercialization model is the development of the 'final operating manual'. The 'final operating manual' details all of the necessary steps to reasonably assure the commercialization of the product.

A 'final operating manual' was not developed for the intelligent ground vehicle due to numerous constraints throughout the process. To name a few, only two subsystems of six were analyzed through the commercialization model. Developing an operating manual including only these two subsystems would have resulted in an incomplete and inaccurate plan for commercialization of the product.

Secondly, the intelligent ground vehicle at the time of writing still hasn't been completed and the team continues to make decisions regarding the design.

Ideally, the team would have made all the decisions regarding the vehicle prior to assembly, as the commercial model indicates as 'best practice.' However, the team did not follow a process oriented toward commercialization and thus did not make all decisions prior to assembly. These two factors combined made assembly of a 'final operating manual' infeasible for the project.

4.3 IGVC team decision-process analysis

Throughout the development of the commercialization model, the IGVC decision process was observed for purposes of comparison against the decision timeline the commercialization model presents. The observation process was informal and documented through detailed meeting notes and minutes. The IGVC team decisions and decision timeline is outlined in Appendix G – IGVC team decision timeline.

The timeline outlined in Appendix G – IGVC team decision timeline is the actual representation of when decisions regarding vehicle configuration and part selection were made. In comparison to the timeline the IGVC team outlined for themselves, the majority of deadlines were not only missed, but missed by weeks and often times months. The IGVC team self-identified timeline is pictured in Figure 19 - IGVC Team Gantt chart and Figure 20 - IGVC Team Gantt . Each deadline that was missed is highlighted in yellow.

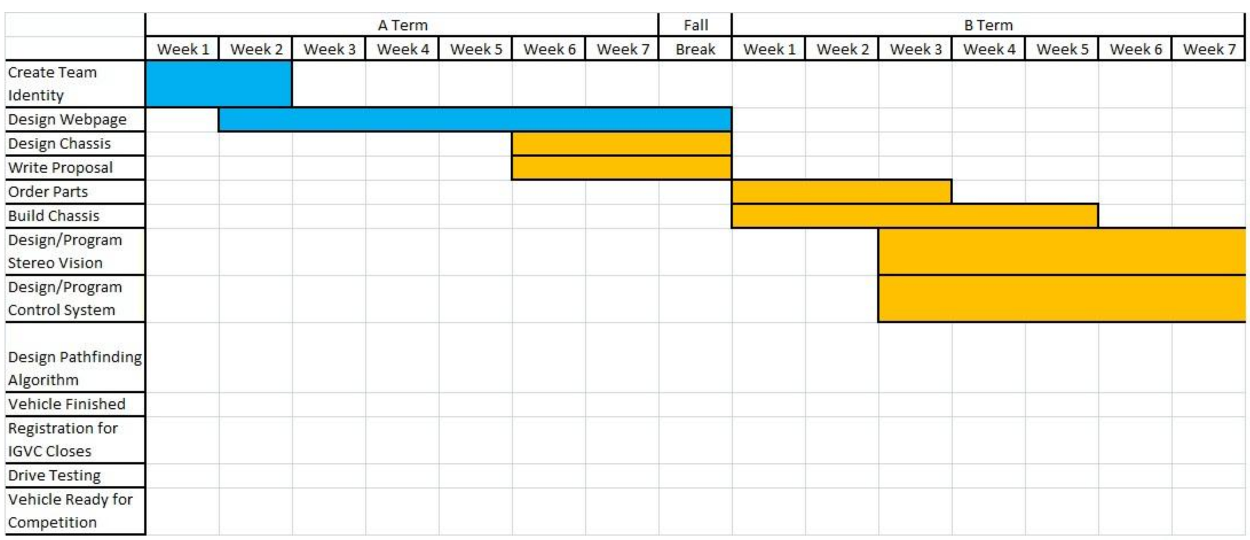

Figure 19 - IGVC Team Gantt chart

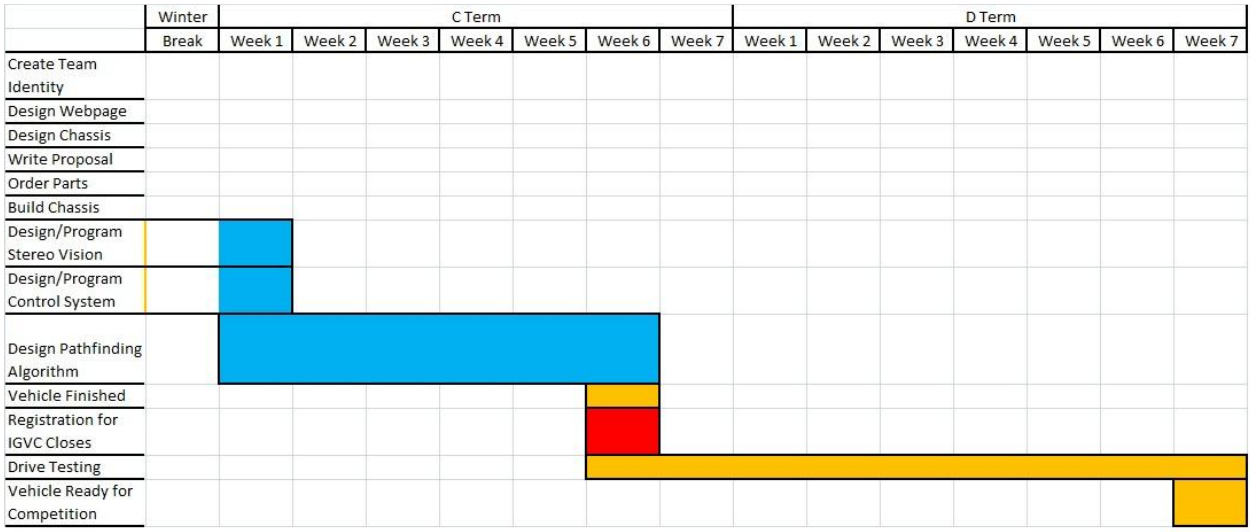

Figure 20 - IGVC Team Gantt chart

While often deadlines are missed, the frequency and number of deadlines that were missed certainly affected many of the decisions the IGVC team made. As decisions were prolonged and delayed, the ability for those decisions to remain pertinent to the design and configuration of the vehicle became strained. As seen in [Figure 21 - Decision cost-influence timeline, the decisions the team was making were further out than they should have been compared to that timeline.

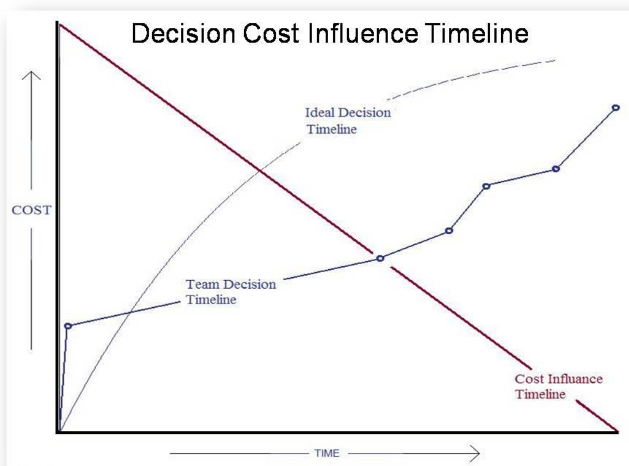

Figure 21 - Decision cost-influence timeline

Plotting the decision timeline of the team versus the ideal decision timeline, as would be exemplified through a process such as that outlined in the commercialization model, adds credence to the method. Furthermore, despite the initial increase in time required to accurately and adequately vet innovative ideas, substantial cost can be saved as a formal process forces teams to a stricter timeline and ultimately results in better decisions.

4.4 Conclusions/Recommendations

Analysis of a 'best practices' approach to decision making versus an informal design approach yielded dramatic results in the categories of influence that were analyzed. Quantitatively, a cost savings for the processing subsystem in the amount of 159% could have been realized had a 'best practices' approach been utilized. Similarly, a cost savings of 73% could have been realized for the stereovision cameras. Amongst other savings, the two subsystems that were analyzed may have been simpler, required fewer engineering hours, and been more viable in production for the commercial space.

With that said, it is important to remember that the IGVC team did a remarkable job in production of an intelligent ground vehicle for competition. Innovations were realized in GPGPU processing, object detection and avoidance, integrated system design, and the overall unmanned ground vehicle robot arena.

Several specific areas have been highlighted below with a few specific conclusions and recommendations.

4.4.1 Timeline development

Through design, development, and testing of the commercial model, timeline adherence and development were realized as a key aspect to a successful, innovative, project. When a timeline is drawn out, deadlines are missed and decisions are not made in a definitive manner, placing the success of the project in jeopardy. The commercialization model attempts to make decisions which will result in the success of a given project in a pertinent and timely manner.

4.4.2 Specification definition

It is critical to build a solid foundation to base design and development decisions. Thus, since the design of a project is often based on a given specification, it is critical to not only identify the key components of that specification, but to also identify all possible configuration options that may effectively and adequately address it.

In the case of the intelligent ground vehicle processing subsystem, the IGVC team quickly decided upon a subsystem configuration. This might have been improved upon had the specification been better reviewed and parts selected in a more orderly process.

4.4.3 Decision criteria

The innovation analysis portion of the commercialization model focuses on identifying a solution for the given problem through a deterministic approach. It is critical to remember however that in order for the decision matrix to be effective the decision criteria for it must be adequately defined. Defining the decision criteria before evaluating the parts and subsystems against the questionnaire is what allows the deterministic decision matrix to work effectively.

Keeping this in mind, it may not be necessary to always utilize a decision matrix to find the ideal solution; however, simply maintaining the necessity to define decision criteria prior to making a decision will result in better selection of parts and definition of configurations and designs.

4.4.4 Commercialization of product through the model

Through the analysis of the two subsystems, results produced were deemed to be valid. The results addressed the need for the subsystems to be cost effective, vendor and delivery conscious, and innovative in nature. The key to ensuring that the criteria of cost, vendors, delivery, and innovation remain pertinent is having an adequate process for development. Whether that process is through a commercialization model as outlined in this report or some other method, it ensures that design and development remains on a deterministic process, enforcing a timeline which is paramount to its success.

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Appendix A – Camera data

Firm Name	Part Number	FPS	Resolution	Res Width	Res Height	ResMult	Resolution Rank	Found Price - 2
Point Grey Research	Dragonfly2 DR2-13S2M	20	1296 x 964	1296	964	1249344	8	$675.00
Scion	CFW-1012C	15	1024 x 768	1024	768	786432	1	$695.00
Scion	CFW-1012M	15	1024 x 768	1024	768	786432	1	$695.00
Point Grey Research	Dragonfly2 DR2-13S2C	20	1296 x 964	1296	964	1249344	8	$745.00
Point Grey Research	Dragonfly2 DR2-HICOL	30	1032 x 776	1032	776	800832	2	$775.00
Point Grey Research	Dragonfly3 DR2-HIBW	30	1032 x 776	1032	776	800832	2	$775.00
Point Grey Research	Flea2 FL2-08S2C	30	1032 x 776	1032	776	800832	2	$795.00
Point Grey Research	Flea2 FL2-08S2M	30	1032 x 776	1032	776	800832	2	$795.00
Point Grey Research	Flea FLEA-HIBW	30	1024 x 768	1024	768	786432	1	$895.00
Point Grey Research	Flea FLEA-HICOL	30	1024 x 768	1024	768	786432	1	$895.00
Basler	scout scA1000-20fm	20	1034 x 779	1034	779	805486	4	$934.00
Basler	scout scA1000-30fm	30	1034 x 779	1034	779	805486	4	$934.00
Unibrain	601b	30	1024 x 768	1024	768	786432	1	$950.00
Unibrain	601c	30	1024 x 768	1024	768	786432	1	$950.00
Unibrain	620b	36	1024 x 768	1024	768	786432	1	$950.00
Unibrain	620c	36	1024 x 768	1024	768	786432	1	$950.00
Point Grey Research	Dragonfly DRAG-HIBW	15	1024 x 768	1024	768	786432	1	$995.00
Point Grey Research	Dragonfly DRAG-HICOL	15	1024 x 768	1024	768	786432	1	$995.00
Point Grey Research	Flea2 FL2-14S3C	17	1392 x 1040	1392	1040	1447680	14	$995.00
Point Grey Research	Flea2 FL2-14S3M	17	1392 x 1040	1392	1040	1447680	14	$995.00
NET GmBH	FO323TB	30	1034 x 779	1034	779	805486	4	$1,029.00
NET GmBH	FO323TC	30	1034 x 779	1034	779	805486	4	$1,029.00
Toshiba Teli	FireDragon CSFX36BC3	36	1024 x 768	1024	768	786432	1	$1,045.00
Toshiba Teli	FireDragon CSFX36CC3	36	1024 x 768	1024	768	786432	1	$1,045.00
PixeLINK	PL-B952F	20	1024 x 768	1024	768	786432	1	$1,116.00
PixeLINK	PL-B953F	20	1024 x 768	1024	768	786432	1	$1,116.00

NET GmBH	FO323B	30	1034 x 779	1034	779	805486	4	$1,143.00
NET GmBH	FO323C	30	1034 x 779	1034	779	805486	4	$1,143.00
NET GmBH	FO323SB	36	1034 x 779	1034	779	805486	4	$1,143.00
NET GmBH	FO323SC	36	1034 x 779	1034	779	805486	4	$1,143.00
Unibrain	701b	15	1280 x 960	1280	960	1228800	7	$1,150.00
Unibrain	701c	15	1280 x 960	1280	960	1228800	7	$1,150.00
Baumer Optronic	TXD08c	28	1024 x 768	1024	768	786432	1	$1,169.00
Baumer Optronic	TXF08c	28	1024 x 768	1024	768	786432	1	$1,169.00
Baumer Optronic	TXF08	28	1032 x 776	1032	776	800832	2	$1,169.00
Allied Vision Technologies	Stingray F-080B	31	1032 x 776	1032	776	800832	2	$1,180.00
Allied Vision Technologies	Stingray F-080C	31	1032 x 776	1032	776	800832	2	$1,180.00
CCD Direct	KP-F83GV XGA	36	1024 x 768	1024	768	786432	1	$1,185.00
Prosilica	GC1020	33	1024 x 768	1024	768	786432	1	$1,190.00
Point Grey Research	Scorpion SCOR-14SOC	19	1360 x 1024	1360	1024	1392640	10	$1,245.00
Point Grey Research	Scorpion SCOR-14SOM	19	1360 x 1024	1360	1024	1392640	10	$1,245.00
Toshiba Teli	FireDragon CSFS20CC2	20	1280 x 1024	1280	1024	1310720	9	$1,250.00
Toshiba Teli	FireDragon SFS20BC2	20	1280 x 1024	1280	1024	1310720	9	$1,250.00
Point Grey Research	Grasshopper GRAS-14S3C	21	1384 x 1032	1384	1032	1428288	11	$1,295.00
Point Grey Research	Grasshopper GRAS-14S3M	21	1384 x 1032	1384	1032	1428288	11	$1,295.00
NET GmBH	FO432B	20	1392 x 1040	1392	1040	1447680	14	$1,332.00
NET GmBH	FO432C	20	1392 x 1040	1392	1040	1447680	14	$1,332.00
NET GmBH	FO432SB	20	1392 x 1040	1392	1040	1447680	14	$1,332.00
NET GmBH	FO432SC	20	1392 x 1040	1392	1040	1447680	14	$1,332.00
Basler	scout scA1390-17fm	17	1392 x 1040	1392	1040	1447680	14	$1,419.00
Basler	scout scA1390-17fc	17	1390 x 1038	1390	1038	1442820	13	$1,444.00
Sony	XCD-SX710CR	30	1024 x 768	1024	768	786432	1	$1,550.00
Sony	XCD-SX90	30	1280 x 960	1280	960	1228800	7	$1,583.00
Sony	XCD-SX90CR	30	1280 x 960	1280	960	1228800	7	$1,583.00
Baumer Optronic	TXD13c	20	1384 x 1032	1384	1032	1428288	11	$1,620.00
Baumer Optronic	TXF13c	20	1384 x 1032	1384	1032	1428288	11	$1,620.00

Baumer Optronic	TXD13	20	1392 x 1040	1392	1040	1447680	14	$1,620.00
Baumer Optronic	TXF13	20	1392 x 1040	1392	1040	1447680	14	$1,620.00
CCD Direct	KP-F140GV	30	1360 x 1024	1360	1024	1392640	10	$1,675.00
Basler	A631f	19	1392 x 1040	1392	1040	1447680	14	$1,679.00
Allied Vision Technologies	Marlin F-080B	23	1032 x 778	1032	778	802896	3	$1,700.00
Allied Vision Technologies	Marlin F-080B 30fps	30	1032 x 778	1032	778	802896	3	$1,700.00
Allied Vision Technologies	Marlin F-080C	23	1032 x 778	1032	778	802896	3	$1,700.00
Allied Vision Technologies	Marlin F-080C 30fps	30	1032 x 778	1032	778	802896	3	$1,700.00
Allied Vision Technologies	Stingray F-146B	15	1388 x 1038	1388	1038	1440744	12	$1,700.00
Allied Vision Technologies	Stingray F-146C	15	1388 x 1038	1388	1038	1440744	12	$1,700.00
Basler	A631fc	19	1388 x 1038	1388	1038	1440744	12	$1,721.00
Prosilica	GC1350	18	1360 x 1024	1360	1024	1392640	10	$1,790.00
Kappa	PS40-1020FW	16	1028 x 1008	1028	1008	1036224	6	$1,796.00
Kappa	PS4-1020FW	16	1028 x 1008	1028	1008	1036224	6	$1,796.00
PixeLINK	PL-B955HF	15	1392 x 1040	1392	1040	1447680	14	$1,916.00
Unibrain	702b	20	1280 x 960	1280	960	1228800	7	$1,990.00
Unibrain	702c	20	1280 x 960	1280	960	1228800	7	$1,990.00
NET GmBH	FO442B	20	1392 x 1040	1392	1040	1447680	14	$2,223.00
NET GmBH	FO442C	20	1392 x 1040	1392	1040	1447680	14	$2,223.00
NET GmBH	FO442SB	20	1392 x 1040	1392	1040	1447680	14	$2,223.00
NET GmBH	FO442SC	20	1392 x 1040	1392	1040	1447680	14	$2,223.00
Allied Vision Technologies	Marlin F-146B	18	1392 x 1040	1392	1040	1447680	14	$2,230.00
Allied Vision Technologies	Marlin F-146C	18	1392 x 1040	1392	1040	1447680	14	$2,230.00
PixeLINK	PL-B958F	15	1600 x 1200	1600	1200	1920000	15	$2,236.00
PixeLINK	PL-B959F	15	1600 x 1200	1600	1200	1920000	15	$2,236.00
Sony	XCD-SX910CR	15	1392 x 1040	1392	1040	1447680	14	$2,450.00
Point Grey Research	Grasshopper GRAS-14S5C	15	1384 x 1036	1384	1036	1433824	12	$2,495.00
Point Grey Research	Grasshopper GRAS-14S5M	15	1384 x 1036	1384	1036	1433824	12	$2,495.00
Basler	scout scA1400-17fm	17	1392 x 1040	1392	1040	1447680	14	$2,549.00
Basler	scout scA1400-17fc	17	1390 x 1038	1390	1038	1442820	13	$2,574.50

Allied Vision Technologies	Stingray F-145B	16	1388 x 1038	1388	1038	1440744	12	$2,750.00
Allied Vision Technologies	Stingray F-145C	16	1388 x 1038	1388	1038	1440744	12	$2,750.00
PixeLINK	PL-B956F	15	1392 x 1040	1392	1040	1447680	14	$2,796.00
PixeLINK	PL-B956HF	15	1392 x 1040	1392	1040	1447680	14	$2,796.00
PixeLINK	PL-B957F	15	1392 x 1040	1392	1040	1447680	14	$2,796.00
Basler	A102f	15	1392 x 1040	1392	1040	1447680	14	$2,890.00
Baumer Optronic	TXD14c	20	1384 x 1032	1384	1032	1428288	11	$2,930.00
Baumer Optronic	TXF14c	20	1384 x 1032	1384	1032	1428288	11	$2,930.00
Baumer Optronic	TXD14	20	1392 x 1040	1392	1040	1447680	14	$2,930.00
Baumer Optronic	TXF14	20	1392 x 1040	1392	1040	1447680	14	$2,930.00
Basler	A102fc	15	1388 x 1038	1388	1038	1440744	12	$2,933.00
Prosilica	GC1380	20	1360 x 1024	1360	1024	1392640	10	$2,950.00
Allied Vision Technologies	Dolphin F-145	15	1392 x 1040	1392	1040	1447680	14	$3,410.00
Allied Vision Technologies	Pike F-100B	48	1000 x 1000	1000	1000	1000000	5	$3,540.00
Allied Vision Technologies	Pike F-100C	48	1000 x 1000	1000	1000	1000000	5	$3,540.00

Appendix B – Camera specifications

Chosen Camera

Flea® 2

ULTRA-COMPACT + VERSATILE + 1394B

POINT GREY

- **12 different models, 0.3 MP to 5.0 MP**
- **Smallest 1394b camera in the world**
- **High speed 1394b 800 Mb/s digital interface**
- **Metal case with locking screw connection**
- **Ideal for industrial machine vision**

With resolutions ranging from 0.3MP (VGA) to 5.0MP and 12 different models to choose from, the compact, versatile Flea®2 camera system is a complete, cost effective and reliable IEEE-1394b solution for demanding imaging applications such as semiconductor inspection and high-speed assembly.

Specification	FL2-03S2M/C	FL2-08S2M/C	FL2-14S3M/C	FL2-20S4M/C	FL2G-13S2M/C	FL2G-50S5M/C
Image Sensor Type	Sony progressive scan interline transfer CCDs with square pixels and global shutter, monochrome or color					
Image Sensor Model	Sony ICX424 1/3"	Sony ICX204 1/3"	Sony ICX267 1/2"	Sony ICX274 1/1.8"	ICX445 1/3" EXview HAD CCD™	ICX655 2/3 SuperHAD CCD™
Maximum Resolution	648x488	1032x776	1392x1032	1624x1224	1288x964	2448x2048
Pixel Size	7.4 x 7.4µm	4.65 x 4.65µm	4.65 x 4.65µm	4.4 x 4.4µm	3.75 x 3.75µm	3.45 x 3.45µm
Analog-to-Digital Converter	Analog Devices 12-bit ADC					
Video Data Output	8, 12, 16 and 24-bit digital data					
Image Data Formats	Y8, Y16 (all models), RGB, YUV411, YUV422, YUV444, 8-bit and 16-bit raw Bayer data (color models)					
Color Processing	On-camera in YUV or RGB format, or on-PC in Raw format					
Digital Interface	Bilingual 9-pin IEEE-1394b for camera control, video data transmission, and power					
Transfer Rates	100, 200, 400, 800 Mbit/s					
Maximum Frame Rate	648x488 at 80 FPS	1032x776 at 30 FPS	1392x1032 at 15 FPS	1624x1224 at 15 FPS	1288x964 at 30 FPS	2448x2048 at 7.5 FPS
Partial Image Modes	pixel binning and region of interest modes via Format_7					
White Balance	automatic / manual / one-push modes, programmable via software					
General Purpose I/O Ports	8-pin Hirose HR25 GPIO connector opto-isolated pins for trigger and strobe (FL2G models only), bi-directional pins for trigger, strobe or serial port					
Gain Control	automatic / manual / one-push gain modes, programmable via software, 0dB to 24dB in 0.04dB increments					
Shutter Speed	automatic / manual / one-push modes, programmable via software, 0.02ms to greater than 10s (extended shutter mode)					
Gamma/LUT	0.50 to 4.00 / programmable lookup table					
Synchronization	via external trigger, software trigger, or free-running					
External Trigger Modes	DCAM v1.31 Trigger Modes 0, 1, 3, 4 and 5 (multiple exposure, 03S2 and 08S2 models only), 14 (overlapped trigger), and 15 (multi-shot trigger)					
Power Consumption	power via Vext GPIO pin or 9-pin 1394b interface: 8 to 30 V, less than 2.5 W					
Dimensions (L x W x H)	29mm x 29mm x 30mm (excluding lens holder, without optics)					
Mass	58g (without optics)					
Memory Storage	(FL2G models only) 32MB frame buffer; 512KB non-volatile data flash					
Memory Channels	3 memory channels for custom camera settings					
Camera Specification	IIDC 1394-based Digital Camera Specification v1.31, compatible with IEEE-1394b and IEEE-1394a interfaces					
Lens Mount	C-mount					
Emissions Compliance	Complies with CE rules and Part 15 Class B of FCC Rules					
Operating Temperature	0° to 45°C					
Storage Temperature	-30° to 60°C					
Warranty	2 year					

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Optional Camera

BASLER SCOUT

scout Series – Are You Looking for a Cost-effective Digital Camera that Supports 100 Meter Cable Lengths?

Basler scout Family – 40 Different Models – Sophisticated in Detail, Versatile, Fully Digital, and Attractively Priced

The Basler scout family is based on a selection of the best Sony CCD sensors and offers a wide variety of resolutions and speeds. The family also includes a high-performance CMOS sensor from Micron. With their new Gigabit Ethernet (GigE) and FireWire-b™ (IEEE 1394b) interface technologies, the cameras in this family are defined by state of the art technology that lets you get the maximum performance from each sensor.

Your benefits from the Basler scout family include:

- Resolutions from VGA to 2 megapixels with either a FireWire-b or a Gigabit Ethernet interface
- 100 meter cable lengths provided by Gigabit Ethernet to give you the highest flexibility
- Up to 12 bit depths and no bandwidth limitation on 8 bit data flow inside the camera
- Free drivers for FireWire and Gigabit Ethernet (GigEVision™)
- Small, rugged housing for easy integration
- Compatible with the newest vision industry standards including GenICam, GigEVision, and EMVA 1288
- 100% quality checked and calibrated to give you consistent performance and reliability

The Basler scout family features a GenICam compliant API and uses new drivers. The FireWire-b cameras are also compatible with Basler's existing BCAM driver and API for FireWire cameras. Along with the drivers, GUI based software is provided that lets users easily set camera parameters, adjust image quality, and control cameras from a remote computer.

Basler scout cameras are a perfect fit for a variety of vision applications including semiconductor and component inspection, manufacturing quality control, food and beverage inspection, intelligent traffic systems, microscopy and medical imaging, biometrics, and many others.

Outstanding Image Quality

The scout family is equipped with seven assorted Sony CCD sensors in mono and color. These sensors were selected to provide outstanding image quality in combination with the scout's read-out and processing electronics. For precise imaging results, all scout cameras run in progressive scan mode.

Users of interlaced analog cameras can easily switch to a scout camera equipped with Micron's MT9V022 CMOS progressive scan sensor.

Gigabit Ethernet (GigE Vision) Drivers

Basler provides its own Gigabit Ethernet drivers for the scout camera family. These drivers will be compatible with the GigEVision standard and optimized for the scout family. To give you maximum flexibility, Basler provides two different drivers:

Filter driver: The filter driver quickly separates incoming packets carrying image data from other traffic on the network and makes the data available for vision applications running on the computer.

Performance driver: By using the performance driver, even demanding applications with multiple cameras, high data rates, or very strict real-time requirements can be supported. When the performance driver is used in combination with a dedicated network interface card (Intel), the load on the host computer's CPU is significantly reduced.

Precise Sensor Alignment

In addition to Basler's standard CTT+ automated quality assurance and calibration system, the scout camera family will be tested and measured with another production tool. This unique tool is an ultra-high precision sensor alignment device. The device automatically mounts the sensor board on the camera's front module in six degrees of freedom with reference to the optical axis. This ensures a constant depth of focus over the whole sensor. For sensors with small pixels (< 5 µm) this is essential for good imaging results.

Appendix C – Processing subsystem configuration options

Team Spec:	Alternative 1	Alternative 2
Overall Objectives:		
1 Object detection accomplished with LIDAR		
2 Line detection accomplished with stereovision		
3 Pothole detection accomplished with stereovision		
4 GPS data taken into account		
5 Motor encoder data processed		
6 Vision systems processing		
7 Drive motor control		
8 Steering motor control		
9 Power system monitoring		
Hardware Required:	**Hardware Required**	**Hardware Required**
1 **cRIO:**	1 **cRIO**	1 **cRIO:**
Pass Lidar information	Process Lidar information	Pass Lidar information
Process GPS Data	Process GPS Data	Process GPS Data
Utilize motor encoder data	Utilize motor encoder data	Utilize motor encoder data
Control drive motors	Control drive motors	Control drive motors
Control steering motors	Control steering motors	Control steering motors
2 **ATX computer to:**		2 **Embedded Computer (PC104):**
Read/Process LIDAR data		Read/Process LIDAR data
Make object detection decisions	Make object detection decisions	Make object detection decisions
Interface with stereovision cameras	Make pathfinding decisions	Interface with stereovision cameras
Make pathfinding decisions		Make pathfinding decisions
3 **nVidia GPGU:**		3 **nVidia GPGPU:**
Process stereovision camera data	Processs stereovision camera data	Process stereovision camera data
System Impications	**System Implications**	**System Implications**
1 Substantial power requirements to support	1 Low power usage	1 Lower power usage
2 Exceptional data processing power	2 Robust/Environment hardend	2 Redundancy
3 Approach allows for later upgrades/expansion	3 Less processing power	3 Expandable
4 Distribution adds redudancy	4 Less expensive	4 Slower data processing capability
5 Not hardened to the envirornment	5 Less sensor usage flexibility	5 Robust/Environment hardend
6 Very expensive	6 Slower data processing capability	6 Moderaly expensive
7 More difficult to program/troubleshoot		

Appendix D – Processing subsystem part data

Embedded PC Solutions:

Manufacturer	Model	Price -1 ($)	Price - 50 ($)	Price - 100 ($)	Description	Processor Speed (Mhz)	Processor	Memory (Mb)	PCIe Slots	Power
iCOP	**eBox-4810**	$331	$312	$305	Slim enclosure, VIA Eden Esther 1.2GHz processor, 1GB DDR2, MPEG4/WMV9 decoding accelerator, 1x EIDE, 1x 10/100 LAN, 1x PS/2 K/B, 1x PS/2 Mouse, 2x USB 2.0 Ports(One in front). Use with EmbedDisk horizontal left RoHS	1200	Via Eden Esther	1000	0	
aValue	EPC-CX700	$381	$364	$356	Onboard VIA Eden V4 CPU, Dual LAN, 1 Mini PCI, Type I/II CF, 1 COM, 3 USB 2.0, Supports 2.5" SATA HDD, Fanless & Single 5V Operation. This kit comes with 1GB memory	1000	Via Eden V4 CPU	1000	0	5v
VIA	AMOS-3000	$399	$379	$369	AMOS-3000 Fanless Ultra Compact Embedded System, C7 1.0GHz, 1x VGA, 1x DVI, 1x COM, 1x GigaLAN, 4x USB, HD Audio, DC-in 12V. No AC adapter, No RAM, See 1EAM1GBAverage power draw: 8.11W, Max: 15.86W. 44 Pin IDE Socket for Flash.	1000	C7 1.0 GHz	1000	0	12v
aValue	**EPC-3711**	$442	$432	$427	Fanless VIA CN700 Eden V4 1GHz Tiny Box PC with AC97 5.1 channel audio, 2xGbit Ethernet, Mini PCI socket, Compact Flash socket, 1xRS232, 1xRS232/422/485, 3xUSB 2.0, 2.5" SATA HDD support, 1xPS/2, VGA. Includes +5VDC power supply. This kit includes a 1GB memory stick. Dimensions: 7" x 4.4" x	1000	Via CN700 Eden	1000	0	5v
SMART	XceedPC/D2	$571	$550	$537	Intel Pentium 4 651, 3.40GHz, 2MB L2 Cache, 800MHz FSB, 1GB DDR2 DRAM, 1x VGA, 1x RS232, 8x USB 2.0, 80GB SATA HDD: 5400	3400	Pentium 4 651	4000	1	12v
Adlink	MXC-2011	$713	$683	$667	Intel Atom N270 fanless configurable controller with 1x PCI slot, One x1 PCIe slot, 2x GbE Ports, 2x RS-232/422/485(jumper selectable, COM1 & COM2), 2x RS-232(COM3 & COM4), 4x USB 2.0 Ports, 1GB DDR2 533MHz SODIMM module	1600	Intel Atom Single Core N270	1000	1	
SMART	XceedPC/D2	$726	$699	$682	Intel Pentium 4 651, 3.40GHz, 2MB L2 Cache, 800MHz FSB, 1GB DDR2 DRAM, 1x DVI- 1x VGA nVidia 8400, 5x RS232, 6x USB 2.0, 80GB SATA HDD: 5400	3400	Pentium 4 651	4000	1	12v

SMART	XceedPC/D3	$753	$725	$707	Intel Core2Duo E6400, 2.13GHz, 2MB L2 Cache, 800MHz FSB, 1GB DDR2 DRAM, 1x VGA, 1x RS232, 8x USB 2.0, 80GB SATA HDD: 5400	2130	Core2Duo E6400	4000	1	12v
SMART	XceedPC/D3	$949	$914	$891	Intel Core2Duo E6400, 2.13GHz, 2MB L2 Cache, 800MHz FSB, 1GB DDR2 DRAM, 1x DVI- 1x VGA nVidia 8400, 5x RS232, 6x USB 2.0, 80GB SATA HDD: 5400	2130	Core2Duo E6400	4000	1	12v

Industrial Motherboard Solutions:

Manufacturer	Model	Price -1	Price - 50	Price - 100	Description	Processor	Memory (Mb)	PCIe Slots	Power
Kontron	886LCD	$154	$146	$145	Motherboard is without CPU, DRAM, Cooler & Accessory Kit 886LCD/ATXU(GV) P-4 with 3x PCI, On board VGA port, resolution up to 2048x1536 (QXGA), Up to 2 GByte PC2100 (DDR266) DDR-SDRAM, AC97 compliant audio, On board Line In/Out, Mic Micro-ATX form factor 24.38 x 24.38 cm (9.6. x 9.6.)	Core2 Duo	4000	3	ATX
VIA	EPIA	$162	$162	$162	1.3 GHZ	Via Epia	1000	1	ATX
Kontron	KT780	$194	$185	$182	KT780 with AMD Core and integrated ATI Radeon HD 3200 graphics with DVI 1x PCI-Express 16X 2.0 Support, 4x PCI, 1x PCI-Express 4x, 12x USB & 6x SATA	AMD Core	4000	1	ATX
Kontron	KT690	$200	$190	$188	2x Lan, 4x SATA300/150 with RAID, 2x COM, LVDS, CRT, DVI, TV-OUT. 2x200-pin DDR2 memory sockets, up to 16GB memory. Use 1JR21GB and 1JR22GB memory.	AMD Turion 64	16000	1	ATX
VIA	EPIA	$225	$217	$211	VB8002 1.6GHz HD Media Mini ITX motherboard	Via EPIA	1000	1	ATX
Ampro	MI-960	$309	$298	$290	MI-960 Mini-ITX LGA775 Intel Core 2 Duo Industrial MB, Q965 + ICH8, LVDS, dual- channel DDR2, Dual GbE, SATA, RoHS	Core2 Duo	4000	1	ATX
Lippert	ITX,M	$924	$841	$813	Includes Mini ITX board, 1.GGhz CPU, and Active Cooler. Cable set and DDR memory must be added	Pentium M	1000	0	5V

					additionally Compatible Memory: 1LDD256, 1LDD512, 1LDD1GB Cable: 1LITXCB				

PC104+ Embedded Solutions:

Manufacturer	Model	Price - 1	Price - 50	Price - 100	Description	Processor Speed (Mhz)	Processor	Memory (Mb)	PCIe Slots	Other Slots	Power
Lippert	CXR-GS45	$762	$744	$727	Cool XpressRunner-GS45 (CXR-GS45) CPU Module with ULV Intel Celeron M722 (1.2Ghz/800MhzFSB/1MB L2 cache) processor and 1GB DDR3 Ram onboard Form factor: PCI/104 Express Commercial Temperature 0C to +60C 1GB DDR3 Ram on board	1200	Celeron	1000	1		5v
Lippert	CXR-GS45	$949	$927	$906	Cool XpressRunner-GS45 (CXR-GS45) CPU Module with SV Intel Core 2 Duo SP9300 (2.26Ghz/1055Mhz FSB/6MB L2 Cache) processor and 1GB DDR3 ram onboard Form factor: PCI/104 Express Commercial Temperature 0C to +60C...1GB DDR3 Ram on board	2260	Core2Duo	1000	1		5v
ICOP	VDX-6354-Plus	$264	$258	$248	Vortex86DX PC/104+ CPU Module with 256MB DDR2 Manual & Drivers CD, Cables, & Screw kit included	500		256	0	1 Header	5V
KONTRON	MOPSlcdLX	$273	$256	$250	Extreme low power fanless PC/104-Plus 500MHz AMD LX800, 16bit Full ISA I/O support(ISA & PCI), DDR-SODIMM, CRT/LCD, 2xCOM, 2xUSB, LPT/IDE/LAN, Approx. 7W low power, Real Time Clock, Watchdog Compatible memory: 1JPM256 (256MB) 1JPM512 (512MB) 1JUG1GB/1JPM124 (1GB)	500	AMD LX800	1000	0	1 Header	5v
aValue	ETM-LX800	$322	$315	$311	500MHz AMD Geode LX800 PC/104+ module with Watchdog timer, LPT, 2xRS232, 4xUSB 2.0, Gigabit Ethernet, PS/2 KB & Mouse, VGA and 18/24-bit TFT LCD. This kit comes with 1GB of memory.	500	AMD Geode LX800	1000	0		5V

KONTRON	MOPS-PM	$784	$754	$717	Intel processor Pentium M with 1.4GHz, 2MB L2 cache (Dothan), ISA&PCI ****EOL as of 12/1/09 LTB: 9/1/2010 LTS: 10/31/2011 For RAM use 1JPM256, 1JPM512 OR 1JPM124. 1JMPMCS cable set HIGHLY RECOMMENDED - 1JPMLCS legacy cable pack also available *******REQUIRES Cooler kit, Please quote 1JMCOOl, MOPS-PM Cooler kit, Active	1400	Pentium M	1000	0	1 Header	5V
Lippert	1.4 Ghz	$1,065	$986	$948	LCD+VGA-CRT/1000/100/10BT/ Dual Channel LVDS/Sound/PCI Bus Power consumption approx 14W (1 DDR SDRAM Module Necessary) All in One CPU Board with Intel Pentium M Processor 738 1.4Ghz 2MB L2 cache and 400Mhz FSB. Includes active cooler Compatible memory: 1LPSOD2 (256MB), 1LPSOD5 (512MB), 1LPSOD1 (1GB) Vertical 44-pin IDE flash modules only	1400	Pentium M	1000	0	1 Header	5v
Lippert	CRR-945GSE	$490	$479	$468	Cool Road Runner 945GSE with Intel Atom N270 (1.6Ghz) processor and 512MB DDR2 Ram onboard. Form Factor: PC/104+ Commercial Temperature Range: 0C to +60C	1600	Atom N270	1000	0	1 Header	5v
Lippert	CRR-PM	$844	$786	$752	Cool Road Runner-PM CPU board with Intel Pentium M745 (1.8Ghz, 2MB L2 cache, 400Mhz FSB) processor PC/104+. Operating Temp -20 C to +60 C Memory used is 1LPSOD2, 1LPSOD5, 1LPSOD1. 1LPMHSA-Active heat sink should be used with this board. Board can be purchased without heat sink. Please specify upon ordering	1800	Pentium M	1000	0	1 Header	5v
Lippert	1.5 GHZ	$926	$862	$824	All in one PCI 104 CPU board with LCD+VGA+CRT. Intel Pent M 745 Dothan 1.8Ghz 2MB L2 cache and 400MhzFSB. Low power consumption max 1GB DDR Ram 6xUSB 2.0 RTC Gold Cap, EIDE, KBD, Mouse, WDOG, CCI-104-bus VGA controller, Gigabit Ethernet 1000/100/10BT, LVDS Interface, AC 97 audio. Includes active cooler Compatible memory: 1LPSOD2 (256MB), 1LPSOD5 (512MB), 1LPSOD1 (1GB) . Vertical 44-pin IDE flash modules only	1800	Pentium M	1000	0	1 Header	5v

Appendix E – Processing subsystem decision matrix

Technology Commercialization
System Decision Matrix

		Original Specification (cRIO, Consumer Computer, Tesla)	Alternative 1 (cRIO Only)	Alternative 2 (cRIO, Embedded PC, Tesla)	Alternative 3 (Embedded PC, Tesla)	.	.
Delivery							
1	The system can be delivered within the allotted timeframe?	1	1	1	1		
2	The system doesn't require sourcing from multiple vendors?		1				
3	Delivery cost is the vendors?						
4	Delivery is guaranteed within your time window?	1	1	1	1		
5	Does the vendor have a proven performance record		1	1	1		
6	Are there additional benefits?		1		1		
	Total	0.2	0.5	0.3	0.4	0	0
Vendors							
1	Are there multiple vendors	1		1	1		
2	Do the vendors provide competitive pricing	1	1	1	1		
3	Do the vendors provide quantity discounts?			1	1		
4	Are the vendors located in multiple geographic regions?	1	1	1	1		
5	The vendors may custom manufacture parts?	1		1	1		
	Total	0.4	0.2	0.5	0.5	0	0
Cost							
1	Is there sufficient ROI for the subsystem?	1	1	1	1		
2	Have the lowest cost parts been selected for the subsystem?				1		
3	Is the subsystem simplified?		1		1		
4	Is the subsystem cost effective?		1	1	1		
5	Part quantity discounts may be negotiated?	1			1		
6	Can the subsystem be manufactured in modular format?	1	1	1	1		
7	Can the subsystem be manufactured at a competitive price?	1		1	1		
8	Can the subsystem manufactured within budget?		1	1	1		
	Total	0.4	0.5	0.5	0.8	0	0
Total System Impact							
1	The subsystem has a total system impact?	1	1	1	1		
2	The subsystem increases performance of the total system?		1	1	1		
3	The subsystem minimizes costs within the total system?		1		1		
4	The subsystem reduces parts needed elsewhere in the total system?		1	1	1		
5	The component interactions within the subsystem are simplified?		1		1		
6	The subsystem requires minimal additional engineering to work with the total system?			1	1		
7	The subsystem uses power efficienty?		1		1		
8	The subsystem minimizes weight?		1		1		
9	The subsystem is small form factor?		1	1	1		
	Total	0.1	0.8	0.5	0.9	0	0
	Grant Total:	1.1	2	1.8	2.6	0	0

Appendix F – Bill of materials

Intelligent Ground Vehicle Competition (IGVC) Bill of Materials - Top Level

Major Assembly	Total Value	Total Actual Cost
Chassis/Drive-train Subsystem	$1,665.20	$1,504.04
Power Distribution Subsystem	$911.96	$0.00
Processing Subsystem	$1,460.22	$879.78
Controller Subsystem	$5,774.00	$0.00
Sensors Subsystem	$10,521.50	$1,961.50
Miscellaneous Items	$5.99	$5.99
Grand Totals	$20,338.87	$4,351.31

Power Distribution Subsystem

Subsystem	Name	Vendor	Donation/ Discount/ Full Price	Part #	Description	Unit	Quantity	Unit Price	Unit Value	Actual Cost
Battery		Optima	Don	D34 - YellowTop	12V, Deep Cycle, Lead-Acid, 750 CCA, Res Cap 120, Cap Rate 55, Int. Resistance .0028 Ohms, 10"L x 6 7/8"W, 7 13/16"H, 42.9 Lbs, SAE Post	ea	4	$227.99	$911.96	$0.00
Distribution	Power Distribution Board									
	Power Conversion Board									
	DC-DC Converters									
	Battery Charger									
	Main Power Switch									
	Electrical Wire									
	Fuses									
	Connectors									
								Totals	$911.96	$0.00

Sensors Subsystem

Name	Sub-Subsystem	Vendor	Donation/ Discount/ Full Price	Part #	Description	Unit	Quantity	Unit Price	Unit Value	Shipping	Actual Cost
Vision	Camera	Point Grey Research	FP	Flea-2	Sony ICX204 CCD, 1/3", 1032x776 at 30 fps, 12 bit ADC, 8-30V power, 2.5 W at 12 V via 1392 firewire, 2 yr warranty, Color, 0-24db gain in .04 increments.		2	$795.00	$1,590.00	$50.00	$1,540.00
	Lens	B&H Photo Video Pro-Audio	FP	PE4818MIY C30405KP	4.8mm focal Length, 55 deg field of view, f/1.8, C-MT, Manual Iris, 2/3"/Reg	ea	2	$135.75	$271.50	$0.00	$271.50
	Software	Point Grey Research	FP	DEVKIT-01-0001	RoHS Development Accessory Kit -01-0001	ea	1	$100.00	$100.00	$0.00	$100.00
GPS	GPS	Sokkia	Don (On Loan)	750-1-0037	Description (from the website): The Sokkia Axis3 is a complete mapping and data acquisition system that provides Beacon, L-Band (OmniSTAR VBS) and WAAS corrections for accurate, real-time positioning for GIS data collection. The lightweight, yet rugged, Axis3 system is easy to use and offers valuable mapping and database functionality. Combined with IMap data collection software and IMap Office, the system is ideal for a variety of GIS/Mapping applications.	ea	1	$2,560.00	$2,560.00		
			\								
Lidar	LIDAR	Sick	Don	LMS 291-S05, 5"	Our non-contact Laser Measurement System LMS Sensors can be used for standard applications involving measurement of objects and position determination, monitoring areas, vehicle guidance and collision control.	ea	1	$6,000.00	$6,000.00		$0.00
								Totals	$10,521.50		$1,961.50

Processing Subsystem

Subsystem	Name	Sub-SubSystem	Vendor	Donation/ Discount/ Full Price	Part #	Description	Unit	Quantity	Unit Price	Unit Value	Shipping	Actual Cost
Computer	10' 1394b		NewEgg	FP	N82E16812189098	Link Depot 10 ft. IEEE 1394b 9 pin to 9 pin Cable Model 1394B-10-9P9P - OEM	ea	1	$4.99	$4.99	$0.00	$4.99
	Motherboard		NewEgg	Dis 8%	N82E16813131359	ASUS P6T LGA 1366 Intel X58 ATX Intel MB	ea	1	$249.99	$249.99	$14.86	$229.99
	Power Supply		NewEgg	Dis 16.67%	N82E16817822004	Diablotek PHD Series PHD650 650W ATX12V V2.2 Power Supply - Retail	ea	1	$59.99	$59.99	$0.00	$49.99
		CPU/Heatsink/Fa	NewEgg	FP	N82E16819115202	Intel Core i7-920 Bloomfield 2.66GHz LGA 1366 130W Quad-Core Processor Model BX80601920 - Retail	ea	1	$288.99	$288.99	$0.00	$288.99
		Ram	NewEgg	Dis 5.26%	DDR3 1600	CORSAIR XMS3 6GB (3 x 2GB) 240-Pin DDR3 SDRAM DDR3 1600 (PC3 12800) Desktop Memory Model CMX6GX3M3C1600C7 - Retial	ea	1	$189.99	$189.99	$0.00	$179.99
		Video1	NewEgg	FP	N82E16814150445	XFX GM210XYNF2 GeForce 210 512MB 64-bit DDR2 PCI Express 2.0 x16 HDCP Ready Video Card - Retail	ea	1	$49.99	$49.99	$0.00	$49.99
		Video2	Nvidia	Don	TESLA C1060	The NVIDIA® Tesla™ C1060 transforms a workstation into a high-performance computer that outperforms a small cluster. This gives technical professionals a dedicated computing resource at their desk-side that is much faster and more energy efficient than a shared cluster in the data center. The Tesla C1060 is based on the massively parallel, many-core Tesla processor, which is coupled with the standard CUDA C programming environment to simplify many-core programming.	ea	1	$550.29	$550.29	$0.00	$0.00
	Crossover Ethernet Cable			FP		Crossover ethernet cable	ea	1	$15.99	$15.99	$0.00	$15.99
	Hard Drive		NewEgg	Dis 18.19%	N82E16822148495	Recertified: Seagate Barracuda 7200.9 ST3500641AS 500GB 7200 RPM SATA 3.0Gb/s 3.5" Hard Drive - Bare Drive	ea	1	54.99	$54.99	$0.00	44.99
									Totals	########		$879.78

Chassis/Drive-train Subsystem

Subassembly	Name	Vendor	Donation/ Discount/ Full Price	Part #	Description	Unit	Quantity	Unit Price	Unit Value	Shipping	Actual Cost
Chassis											
	Lexan Panels	MCC		See Chassis - Lexan Panels				$0.00	$0.00		
	Aluminum Bars (by 6' lengths)	MSC	Dis -10%	See Chassis - Aluminum Bars	1" OD 6' ALM TB 6063 1/8" W	ea	20	$25.25	$505.00		$454.50
	Aluminum Paneling	MCC		See Chassis - Aluminum Panels			1	$72.93	$72.93		
Drive-train											
	Steering Shaft Radial Bearings	MCC		6384K363			2	$9.66	$19.32		
	Steering Column Turntable	MCC		6031K18			1	$3.51	$3.51		
	Steering Motor	The Robot	FP	ML-42-24	ML-42 24:1 Geared Motor	ea	1	$59.95	$59.95	$0.00	$59.95
	Drive motor	The Robot	FP	NPC-T64	Our most popular seller. This unit combines a strong motor with a durable 20:1 gearbox in a light package. In most applications it can handle 36 volts, increasing rpm by 50%and hp by 60%. If you are using this motor in a combative situation, mounting accuracy is critical. Holes must align so there is no overstressing, and bolts must penetrate 3/4" deep. Not recommended as a weapons motor.	ea	2	$286.00	$572.00	$45.36	$572.00
	Motor Speed Controller	Digikey	Dis-15%	MDL-BDC24	MOD Brushed DC Motor Controller W/Can.	ea	2	$85.00	$170.00	$7.29	$170.00
	Wheels	Wesco	FP	WES120-2	Wesco Pneumatic Wheel, 12" with 3/4" axel bore		3	$64.98	$194.94		$194.94
	Steering support Plate Top and Bottom (24x12 3/8)	MCC		9072K19			1	$54.06	$54.06		
	Steering Column Drive Rod 1/2" x 12" steel rod	MCC		7936K331			1	$13.49	$13.49		
					Total				$1,665.20		$1,504.04

Processing Subsystem

Name	Sub-Subsystem	Vendor	Donation/ Discount/ Full Price	Part #	Description	Unit	Quantity	Unit Price	Unit Value	Actual Cost
cRIO Chassis		National Instruments	Don	779999-01	cRIO-Chassis	ea	1	$2,000.00	$2,000.00	$0.00
	cRio Controller	National Instruments	Don	cRIO-9074	The National Instruments CompactRIO programmable automation controller is an advanced embedded control and data acquisition system designed for applications that require high performance and reliability. With the system's open, embedded architecture, small size, extreme ruggedness, and flexibility, engineers and embedded developers can use COTS hardware to quickly build custom embedded systems. NI CompactRIO is powered by National Instruments LabVIEW FPGA and LabVIEW Real-Time technologies, giving engineers the	ea	1	$1,600.00	$1,600.00	$0.00
	cRio Module	National Instruments	Don	781093-01	NI PS-15 Power Supply, 24 VDC, 5A, 100-120/200-240 VAC Input, Spring Clamp Terminals	ea	1		$0.00	$0.00
	cRio Module	National Instruments	Don	779013-01	cRIO-9201 8-Ch, ±10 V, 500 kS/s, 12-Bit Analog Input Module, C Series	ea	2	$379.00	$758.00	$0.00
	cRio Module	National Instruments	Don	779103-01	NI 9933 37 PIN D-SUB Connector Kit	ea	2		$0.00	$0.00
	cRio Module	National Instruments	Don	779883-01	CompactRIO and LabView Development Fundementals Course Kit	ea	1		$0.00	
	cRio Module	National Instruments	Don	779787-01	cRIO-9403 C Series 32-Ch, 5 V/TTL Bidirectional Digital I/O Module	ea	2	$369.00	$738.00	$0.00
	cRio Module	National Instruments	Don	779004-01	cRIO-9472 8-Channel 24 V Logic, 100 µs, Sourcing Digital Output Module	ea	1	$99.00	$99.00	$0.00
	cRio Module	National Instruments	Don	779891-01	cRIO-9780 4-Port, RS232 Serial Interface Module for CompactRIO	ea	1	$579.00	$579.00	$0.00
								Totals	$5,774.00	$0.00

Appendix G – IGVC team decision timeline

IGVC Decision-Making Timeline				
			Actual	
Decision Making Timeline			**Date/Meeting**	
1	Initial group establishment meeting		8/20/2009	Job Scoping
	Developed meeting schedule, set group standards, decided on timeline format, and decided on agenda/minutes format, discussed/recorded need for project, developed deliverables for project			
2	Timeline development			
	Developed rough timeline, website deliverable for beginning of November, discussed ways to increase sponsorship, discussed ways to encourage team cohesiveness and effective collaboration			Cognitive Leadership Style
3	Discuss sensor subsystem possibilities		9/10/2009	
	3a	Possible methods for detecting objects include: lidar, gps, stereo vision		Project Charter
	3b	Discussed usage of JAUS, which is a competition requirement		
4	Discussed using sensors already available from the Electrical and Computer Engineering Department			Financial Management
5	Developed list of competition spec's and desired feature specs for vehicle			

6	Developed list of group skill set and made available to everyone		9/14/2009	
7	Discussed sensor technologies currently available			Functional Analysis
	7a	Vision: CMOS, CCD		
	7b	Controls: Full computer, cRIO, laptop		
	7c	Battery: NiCD, NiMH, Lithium Ion (expensive), Lead Acid (cheap)		Concept Tree
	7d	Object detection: lidar, camcorders, compass		
8	Discussion prioritizing subsystem decision making		9/21/2009	Standard Solutions
	Priority list: chassis, sensors, power, control systems			
9	Presentation on drive-system design			Innovative Solutions
	Pugh analysis completed for each drive system presented. Two drive wheels with castor received highest subjective weighted score.			
10	Presentation on cRIO system			
	Discussed utilizing cRIO system in conjunction with GPU to enhance sensor system capability/processing power. Distributed control system discussed/generally decided upon			Pugh Analysis
11	Presentation on utilization of GPU for lidar			
	Some discussion on whether will be able to fully utilize GPU processing power, cost of this option, and need for this option			Develop Solution
12	Decision to use GPU & cRIO for vision processing		9/24/2009	
13	Discussion of chassis/drive train		9/28/2009	Value Stream Wrap

	13a	Swing arm/axle suspension - pros/cons weighed		
		General discussion focused on a 'feeling' for what would be best. No analysis completed		Work Cell Design
	13b	Front caster evaluated		
		Positioning of sensor systems rules out need for caster suspension.		
	13c	Wheels discussed – three wheel, bicycle, custom design		
		Wheel types discussed, although not weighed in a decision matrix. Ultimate decision was made to use a wheelchair wheel because of cost, availability, and ease of incorporation into vehicle design.		
	13d	Chassis options presented: Six wheel, hinged base, 2 wheel/1 caster, 4x4 drive train		
14	Evaluated spec compliance so far		10/1/2009	
15	Proposal sent to nVidia for sponsorship to acquire GPGPU			
16	Discussed chassis proposal, decided on 3 wheel			
	Decided on 3 wheel design with caster. No decision matrix was used, only prior knowledge of successful past vehicle designs.			
17	PDR developed for review		10/8/2009	
	Continued to discuss chassis options, suspension type, and weather hardening options.			
18	Decided to utilize wheelchair motors			
	This option was chosen without a decision matrix because of cost and already included parts (wheels, controllers, encoders, etc.)			
19	Assigned responsibility for subsystems to team members		10/12/2009	

	Each team member became the primary point-person for a subsystem, and the secondary point-person for another subsystem.		
20	Developed Gantt chart to aid in completing tasks	12/15/2009	
21	Develop GPS proposal	10/28/2010	
	Some discussion occurred on various GPS types. Team elected to solicit sponsorship for the most accurate GPS that could be found.		
22	Decided on stereo vision system		
23	Lidar system donated		
24	Unsure on what size aluminum stock to use - cost not factor, chose heavier	12/12/2010	
25	Decided on Lead Acid Batteries, unless another option donated	12/12/2010	
	Other batteries were not priced out, nor were a decision matrix utilized in the battery selection process. Cost was the predominant factor		
26	Specification were outlined for main computer & purchased parts	1/20/2010	
	No calculations were made to determine loading or power usage. Only the basic features needed to run the robot were factored into the selection process.		
27	Chassis finalized, construction not begun - behind IGVC timeline	1/20/2010	
28	Have been practice welding for previous two weeks. Actual welding has not yet begun. No Stress analysis done to determine the strength of bolts needed.	2/10/2010	
29	Ken Stafford believes can use NiMH batteries because required run time is relatively short. A123 does not look like they will sponsor the vehicle--will not be using LiPOe. Discussed using an dc-ac converter to power the computer.	2/10/2010	

30	Using a dc-ac inverter may introduce substantial inefficiency. Team would still like to use dc-ac converter. Computer spec did not encompass power issue/cost of dc-dc converter. Depending on how much power computer will use, will determine how important efficiency issues are (Ciraldi).	2/10/2010	
31	Ordering 2 motor controllers (Jaguars) so that can begin working with them in conjunction with the cRIO	2/10/2010	
32	Ordered ATX computer parts	2/12/2010	