High Compliance All-Terrain Transport and Heavy Cargo Hybrid Bicycle

by

Andres Pino
In collaboration with
Orlando Soto

Submitted to the Department of Mechanical Engineering in Partial Fulfillment of the Requirements for the Degree of

Bachelor of Science

at the

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ABSTRACT

This research involved the design and manufacture of a prototype for a hybrid bicycle system. The design called for a vehicle capable of being used in a mode where normal bicycle operation is possible while being reconfigurable into a cargo carrying configuration where both wheels are coaxial. The simplification of the process by which the device could change from one mode to the other and the robustness of the system as a whole were set as primary design criteria. This design would allow for the transportation of individuals and cargo under varying situations, including the evacuation of a wounded individual when in cargo mode.

The success of the prototype proved the value of the concept and its possible applications in military, urban, and outdoor environments. Testing also showed that further research into refining the cargo transport's driving dynamics and the manufacturing of the most critical components is merited.

Thesis Supervisor: Ernesto Blanco
Title: Adjunct Professor of Mechanical Engineering

1.0 Introduction

The bicycle has been a fundamental technology ever since its appearance nearly 200 years ago. The modern bicycle showcases great advances in the way new materials and manufacturing technologies can serve to refine a fundamental concept. Nevertheless the actual design of the bicycle remains fairly unchanged from its original form and its use has been limited to the transportation of humans and limited cargo. This has constrained the applications which can be fulfilled by the bicycle as a mode of transport.

The goal of this research has been to develop a variation of the bicycle concept capable of not only fulfilling the applications commonly required of the technology but also be reconfigurable into a form suitable for carrying loads of much larger volume and weight than a bicycle, much in the form of a rickshaw. This ability to change into a cargo carrying configuration makes it possible to also transport a passenger or wounded individual. This feature could prove especially useful for military and emergency rescue personnel as a means of quickly reaching a wounded individual and then being able to transport that person single handedly. The design, while adding minimal mechanical complexity to the modern common bicycle, brings with it the added capability to carry substantial loads in an affordable and familiar form for military personnel, search and rescue, outdoorsmen, and many people in developing nations for whom bicycles are already the only affordable means of transportation.

In this manuscript I will present a brief history of the bicycle as well as its current design features and applications and proceed to discuss the evolution of our design and prototype. Where most advances in the design and manufacture of bicycles in over a century have focused on refining basic functions and materials, our device expands the applications of the bicycle beyond its current role in transportation while requiring minimal modification to the basic design. It is the proposal of a bicycle variation capable of fulfilling this need for human powered transportation in various configurations and roles that is the goal of this research.

1.1 The History of the Bicycle

The exact origins of the bicycle have been long debated but the earliest known evidence of a clear predecessor to the modern design is accredited to Baron Karl von Drais in 1816. His *draisine* was a form of *pushbike* which moved by the force of the rider's feet pushing off of the ground. This early design was not only uncomfortable to ride but proved impractical as a means of transportation during the time. In 1850, French inventors Ernest Michaux and Pierre Lallement took a different approach by adding pedals to a large front wheel. Their creation inspired the all metal, rubber tire, ***high wheel*** bicycle of 1870, designed by James Starley. The high wheel concept had multiple safety and ride comfort issues inherent to the rider's height off the ground and the fact that both steering and driving force where being done by the front wheel. It was not until James Starley's nephew, J.K. Starley, together with J.H. Lawson and Shergold, developed the chain powered real wheel drive mechanism that the modern bike began to take shape. The Rover, an 1885 model by Starley, is often said to be the first recognizable modern bicycle.

Figure 1: A couple riding a two person variation of the high wheel "bicycle", 1886.[1]

The late 19th century saw the development of numerous refinements including the freewheel, chain-pull brakes, and derailleur gears, all of which greatly improved the basic design and are still in use today. During this *Golden Age of Bicycles*, the raw concept set by Starley became more appealing to the masses as many of the safety and ride comfort issues where addressed. By the turn of the century the bicycle had become popular both in America and in Europe and activities such as racing and touring quickly gained a following.

[1] Photographs and information from http://en.wikipedia.org/wiki/Bicycle

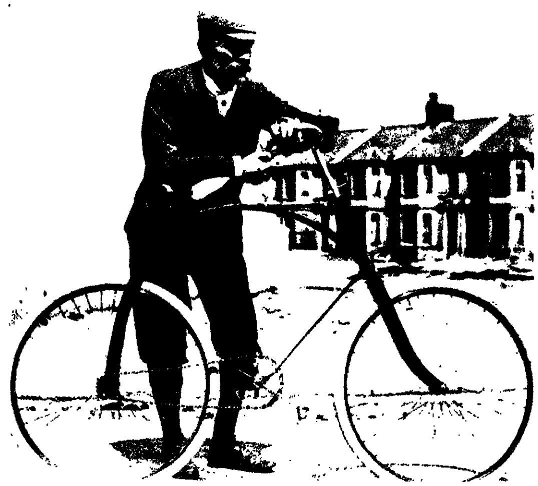

Figure 2: Predecessor of the Starley diamond frame common today, late 19th century

During the twentieth century the bicycle became the standard form of transportation for millions of people around the world. The advent of the motorcycle and automobile led to declines in the use of human powered devices in many western countries, but it continued as a mainstay of transportation in many countries such as China, India, Germany, and Denmark. During the 1960's, health awareness and environmental concerns led to somewhat of a rebirth of cycling in North America, which fueled many innovations. Task specific bicycle designs like the mountain bike and the city bike are products of this late 20th century boom.

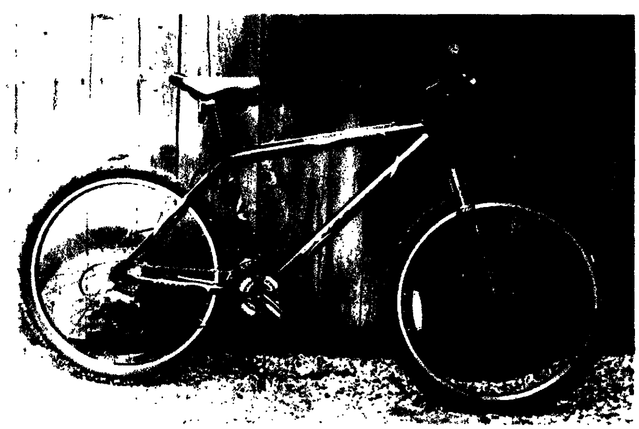

Figure 3: Modern mountain bike.

1.2 The Bicycle and its Applications

Throughout its history the most common use of the bicycle has been to transport a single individual. Transportation can nevertheless take many forms as the needs of a specific scenario or terrain can greatly affect the design that would best fill those needs. Task specific bicycle designs such as racing, mountain, touring, or utility bikes have many refinements that greatly improve performance for a particular terrain or situation but ultimately are also limited to the role of transporting a single person. Brake design, frame material and design, suspension systems, and additional accessories are all choices that can make a bicycle more suitable for certain situations than others. Nevertheless the use of the bicycle to carry cargo has been limited to cumbersome attachments that reduce the performance of the bicycle at its fundamental task of transporting an individual.

Figure 4: Dutch utility bicycle

The most common form of carrying cargo on a bicycle is by attaching baskets or supports to which a package can be fixed at the front or rear of the frame. This method proves to be ideal for small loads, usually no heavier than what an adult individual could carry by hand or in a backpack. In order to increase the cargo capacity some manufacturers produce trailers that can be attached to a bicycle. These trailer systems make carrying large loads possible but add length and additional wheels to the vehicle, changing its driving dynamics even when cargo is not being carried.

Figure 5: Example of accessories designed to carry cargo.

The ability to carry a load as large as an adult passenger has therefore been limited to robust bicycle/rickshaw combinations that are limited to paved roads and urban environments. Carrying loads of this size in a vehicle that is limited to two wheels has therefore been one of the few niches that available bicycle accessories and attachments have not been able to fill. It was our goal in this research to fill that need by designing a system that can perform in multiple roles while maintaining the full functionality expected of each configuration.

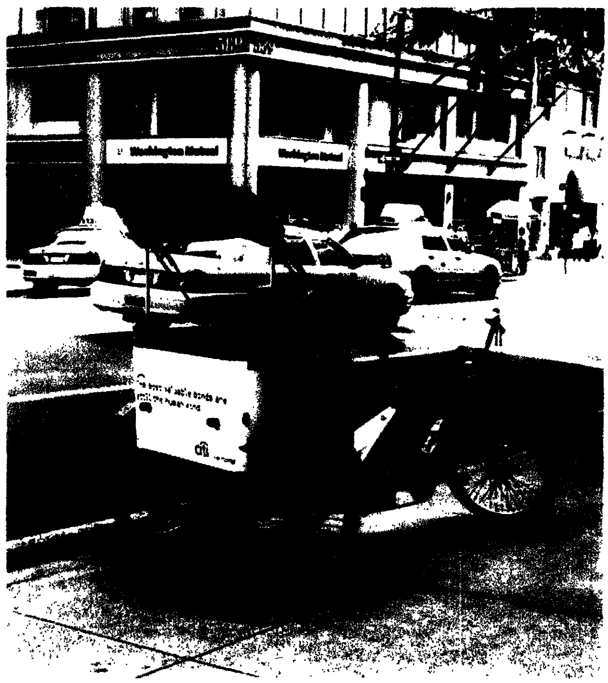

Figure 6: Bicycle/Rickshaw combination (note the added bulk).

One particular application of the bicycle that was of interest to our research was the use of bicycles in military scenarios. In the late nineteenth century, several leading nations created military units that took advantage of the mobility the bicycle offered. In Italy in 1870, sharp shooters were assigned to bicycle units which provided rapid and silent mobility to varied terrain. In 1887 in France, regiments of soldier cyclists were created which led to the development of a folding bike design capable of being stored in a backpack. By 1891, the United States had begun to adopt bicycles for numerous applications within the military as the maintenance and care advantages over horses became apparent. With the advent of the automobile and the motorcycle the use of military bicycles has all but disappeared but the need for a high compliance human powered transport has not.

Figure 7: The 25^{th} U.S. Infantry Bicycle Corps in 1896.[2]

2.0 Modern Bicycle Design

Hundreds of variations to the commonly recognized bicycle exist. Even though the diamond frame designed by Starley is still the most common geometry, many other frame geometries are used today and the design of specific components is also tailored to a bicycle's intended use or intended user. Racing bikes for example emphasize aerodynamics and use modern materials such as carbon fiber to reduce weight and increase rigidity. Mountain bikes, on the other hand, count on suspension systems and specially designed tires to tame unforgiving terrain.

The ergonomics of the handlebars, pedals, and other human interface components also reflect specific needs; some extreme designs depart from the norm as far as removing the handlebars entirely, or employing the use of hand pedals for the driving force. Nevertheless none of these radical designs or task specific models have the ability to change from a fully functional bicycle to a cargo carrying configuration. In the following sections I will describe in detail the geometry of the common diamond frame in order to then show how a reconfigurable bicycle can be made with minimal modification to the frame itself while maintaining compatibility with many available bicycle parts.

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[2] Photograph and information from "An Army on Bicycles", *Invention & Technology*. 1994, Vol.10, #2. p.49.

2.1 Frame Design Details

The diamond frame is by far the most common geometry of bicycle frame. This simple design can be found manufactured out of many modern materials including steel, aluminum, or carbon composites but has been in use for over a hundred years. While variations in the angles of the various segments is common, the concept of a head tube for holding the front fork while the rear hub is attached to the frame itself is nearly universal.

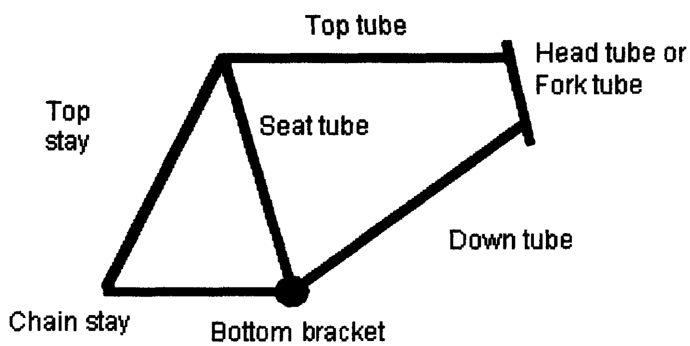

Figure 8: Common diamond frame[3]

The head tube was of particular interest during the design process since it carries heavy loads while serving as one of the most important moving connections in the bicycle. A device called a headset is inserted between the heat tube and the fork. The head tube and headset assembly then acts as a thrust bearing which not only provides the rotation necessary to steer the front wheel but also holds a substantial amount of load do not only to the riders white but to forces transmitted by the terrain.

[3] Diagrams from http://travel.howstuffworks.com/bicycle.htm

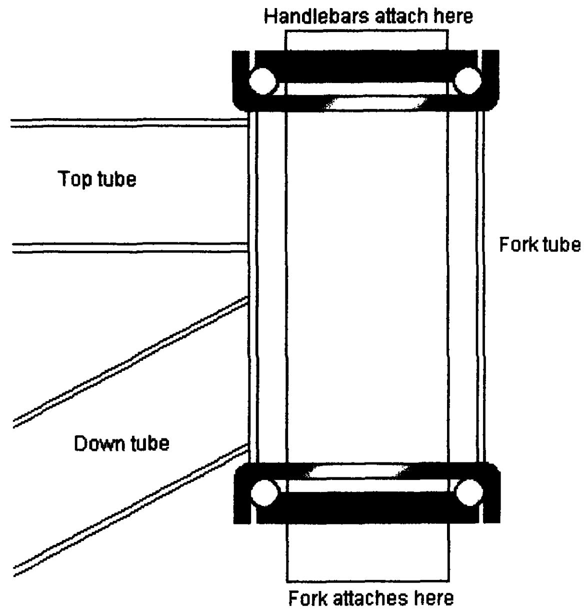

Figure 9: Diagram of head tube

3.0 A High Compliance Hybrid Bicycle Design

3.1 Concept

The initial concept for our design came from the idea of a bicycle with a symmetrical frame that could be reconfigured quickly through the use of a locking mechanism. In other words, we considered the possibility of a bicycle frame that replicated the front head-tube and fork assembly for the rear wheel instead of attaching the rear wheel directly to the frame. With such a frame, both wheels would be able to rotate if allowed that degree of freedom. If both front and rear forks were then fitted with a locking device we could lock the rear wheel in its usual in-line position and leave the front wheel free which would allow for normal bicycle operation. If we then instead lock both wheels in a position where they are perpendicular to the frame, a device much like a wheel barrow or rickshaw could be produced with limited additional parts.

3.2 Design Criteria

The design goals we established were that the device be capable of performing as a rigid frame mountain bike as well as a rickshaw capable of carrying cargo or a second individual. In order for the design to be considered feasible we felt that there were a few criteria that needed to be met. First of all we concluded that a symmetrical frame would provide several advantages when in the cargo carrying configuration. Since the frame itself serves as part of the cargo area, maintaining symmetry would make affixing the load to be carried far easier. In addition, the extensions needed to steer the rickshaw and expand the cargo area would have to be integrated into the frame in order to avoid disturbing the rider while retracted in bicycle mode.

Another important criterion to the success of the design was that the process by which the device is changed from bicycle to the cargo carrying configuration be kept to a minimal number of steps. If going from bicycle to rickshaw configuration was an arduous process then certain applications we envisioned for the system, such as rescuing a wounded soldier, would be difficult to achieve. We approached the problem by finding key components that the geometry in each configuration would demand. By trying to minimize the amount of transformation necessary we were able to reduce the process to 5 steps. First the front wheel is rotated to a position perpendicular to the frame and locked in position. Secondly, the rider dismounts and unlocks the rear wheel so it can be rotated to the same position as the front wheel and is also then locked in place. Then the chain is disengaged and stored. The four extendable arms that will provide steering and an expanded cargo area are then deployed, and finally the fabric "hammock" that makes up the cargo floor is unfolded and fixed to the cargo arms. The figures below show the first proof of concept model that was made at different stages of the conversion process. In figure 10 we can already see the resemblance of the reconfigured frame to a rickshaw or wheelbarrow.

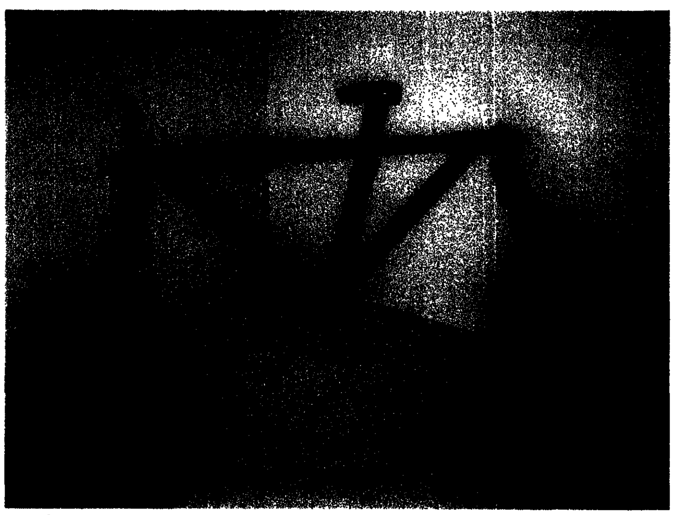

Figure 10: Early model in bicycle configuration.

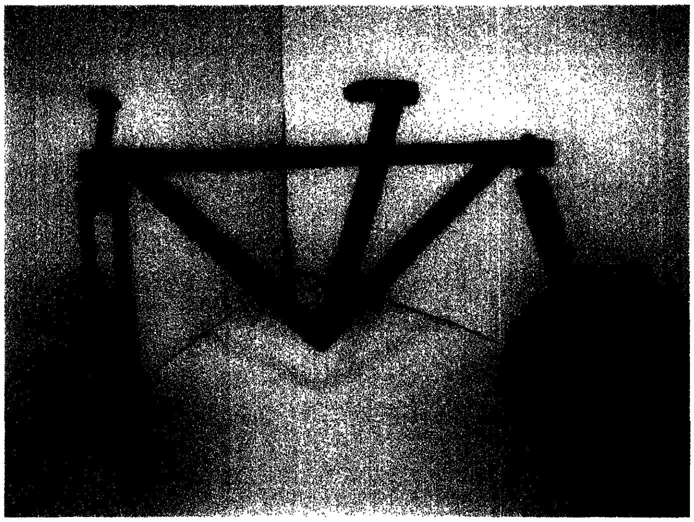

Figure 11: Front fork locked in perpendicular position.

Figure 12: Cargo carrying position (steering and cargo bay arms not shown).

Perhaps the most critical factor to the performance of our device was ensuring that the frame and parts used throughout were capable of handling loads of at least 200 pounds in both configurations. In order to ensure that a person could be carried as a passenger when in the cargo configuration, the frame, headset, and additional parts would have to be able to withstand a grown man's weight and rough terrain. Because the cargo configuration is the bicycle frame on its side, we had to ensure that the frame welds could withstand loads from multiple directions. In addition, forks, bearings, and material for custom parts had to be chosen appropriately.

3.3 Design Details

From our early design meetings it was apparent that the frame for our hybrid bicycle would have to maintain a certain amount of symmetry about the center line of the top bar. In order for the cargo configuration to be easy to operate and familiar to the user the frame had to fulfill all the requirements of a bicycle frame but also had to be quickly recognizable to the user as a cargo carrying device when the bicycle is converted. Another advantage of mirroring the angle and arrangement of the head tube, top tube, and down tube at both ends of the frame was that it maximized the useable area for anchoring cargo or an individual. In order to ensure proper driving dynamics, a mountain bike was used as the template from which the geometry was derived. The front end of the mountain bike frame was therefore duplicated for both ends of the hybrid frame. The end result was a frame three inches longer than a standard frame from the bottom bracket to end of the rear fork.

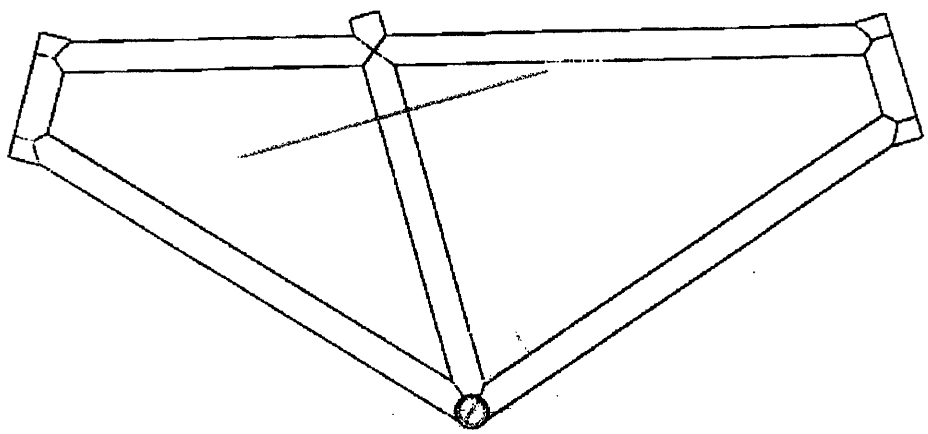

Figure 13: Schematic of the symmetrical hybrid frame.

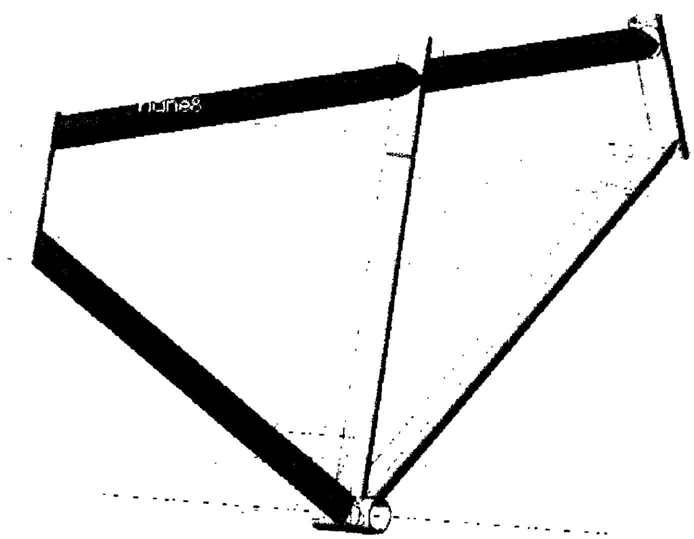

Figure 14: Isometric view of frame solid model.

In order to provide the functionality required of the cargo mode, arms for steering the device and additional parts to furnish the cargo area where necessary. In order to accommodate the length of steering arms required when in bicycle mode, it was necessary to design them to be extendable and retractable. When in bicycle mode the arms where then collapsed and stored against the frame but would then be easily deployed and locked in position for the cargo configuration. A telescoping mechanism was considered in the initial design but it was later changed to the folding mechanism seen in the figure below. One advantage of this design was that the direction of the forces applied to it during it operation would be in the direction in which the armature is strongest. Another advantage would be the ease in which the armature could be locked in place which was one of the difficulties we encountered with the telescoping design.

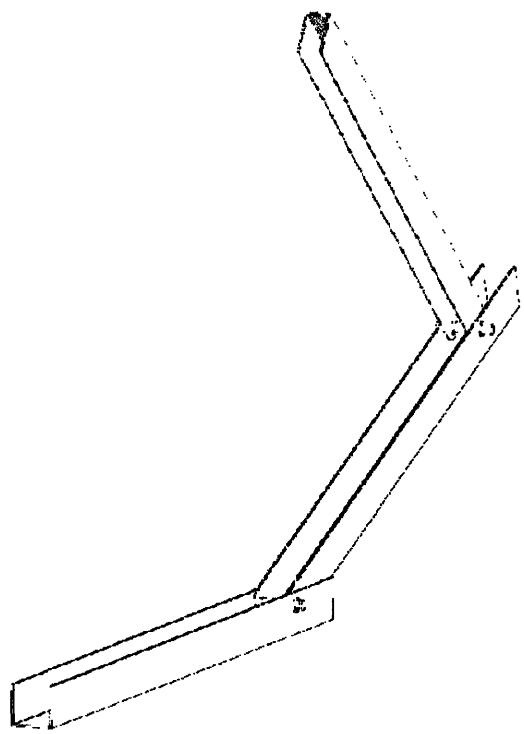

Figure 15: Model of the foldable steering handles.

Due to the geometries of both configurations, we concluded that using a fork such as those used for the front wheel of common bicycles would be the best solution for allowing the back wheel to rotate. In addition using a fork assembly that would be nearly identical in the front and rear would simplify the process of designing a locking mechanism capable of holding the fork in place under heavy loads while providing free movement of the front fork when desired. It was also decided that existing bicycle parts should be used as much as possible throughout. By making the design compatible with common parts such as the seat, handlebars, pedals, headsets, wheels, tires, breaks, and bottom bracket, the device would benefit from the decades of design evolution all of these products have endured while minimizing the difficulties in repairs and replacements that custom parts would imply.

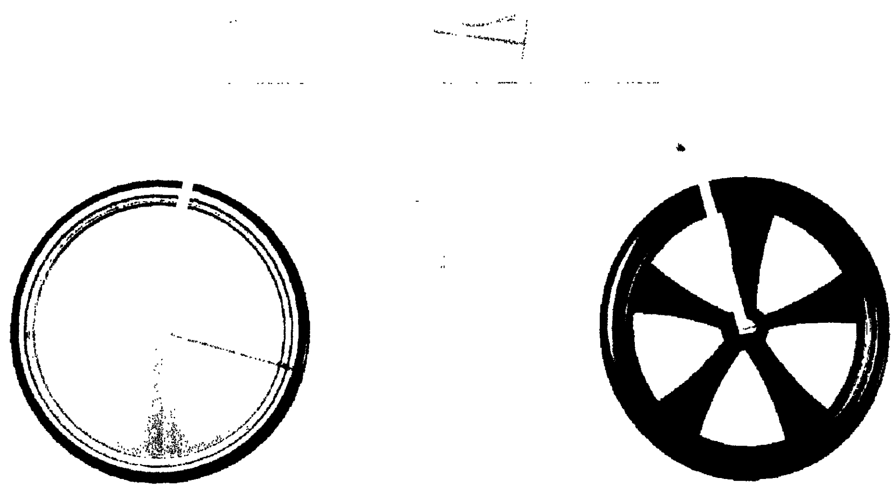

Figure 16: Solid model of the alpha prototype.

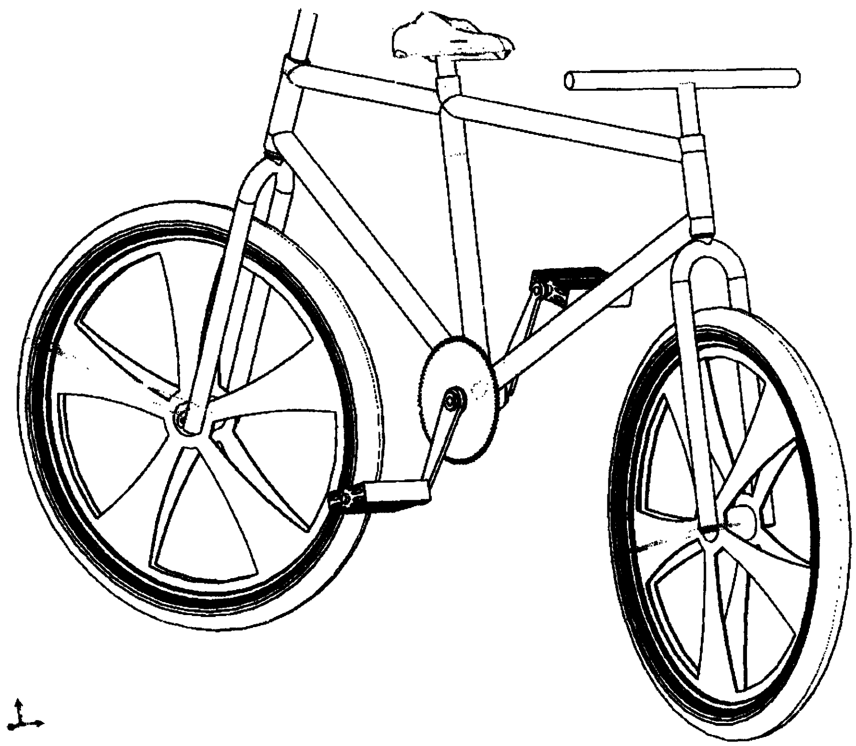

Figure 17: Sketch of prototype showing the use of existing parts throughout.

The design for the locking system that would fix the forks in various positions was simplified to a deadbolt design integrated into the top tube at the intersection with the head tube. The sliding pin mechanism would provide the strength necessary to carry the loads in both bicycle and cargo positions while providing ease of use. The front fork would then be given only one locking position, perpendicular to the plane of the frame, for when in cargo configuration, but would also be allowed to rotate freely when not in that position to ensure proper operation in bicycle mode. Since the rear fork is never required to rotate freely it was given two locking positions. In one position the rear fork is in the same plane as the frame and the gears so that the chain can be attached and the device driven as a normal bicycle. In the other position the rear fork is perpendicular to the frame. In this position the chain must be removed and when both forks are then locked in this perpendicular position, we get a coaxial arrangement of the two wheels, as with a rickshaw or wheelbarrow as previously stated. In order to allow for the removal of the chain, a clasp was designed into one of the links of a common bicycle chain. This clasp link would provide easy access to removing and replacing the chain.

4.0 Prototype Construction

In order to properly test the capabilities of our design it became apparent that a fully functional prototype was necessary. By using existing bicycle parts wherever possible, the need for custom machining was reduced to the frame itself and the retractable armatures that would provide steering and cargo area when the bicycle is reconfigured. In order to ensure the frame was constructed accurately, I transferred the measurements derived from the mountain bike and solid-model onto a large sheet of paper at one to one scale.

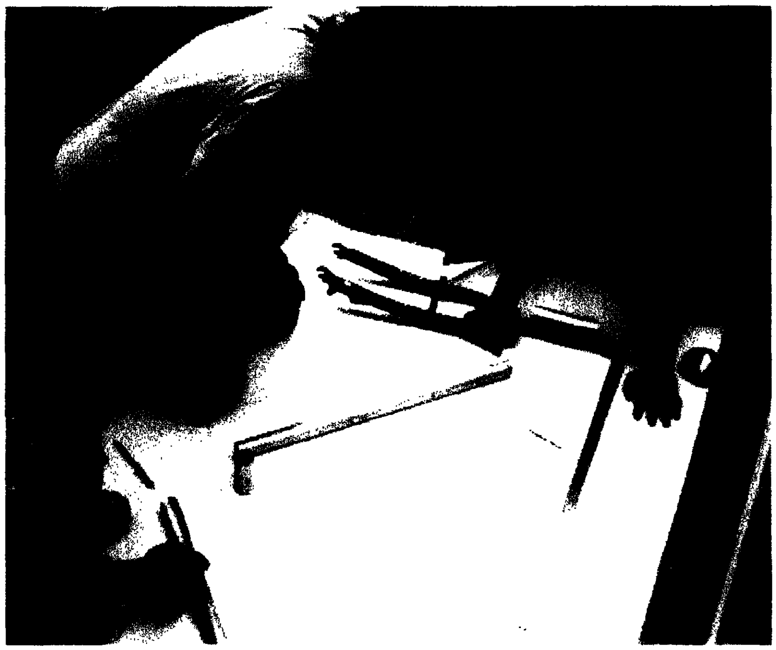

Figure 18: Tube lengths were verified on a 1:1 scale sketch.

Using this paper template, aluminum tubing was cut to match each specified length and arranged on the template to ensure the geometry was accurate. Of particular interest was the rake angle of the head tubes which was set to ten degrees. In order for the device to work well in rickshaw mode the rake angle had to be kept to a minimum while removing it entirely would make the bicycle configuration unwieldy to steer since it would cancel the effects of *precession* that allow for a bicycle's self steering when in motion.

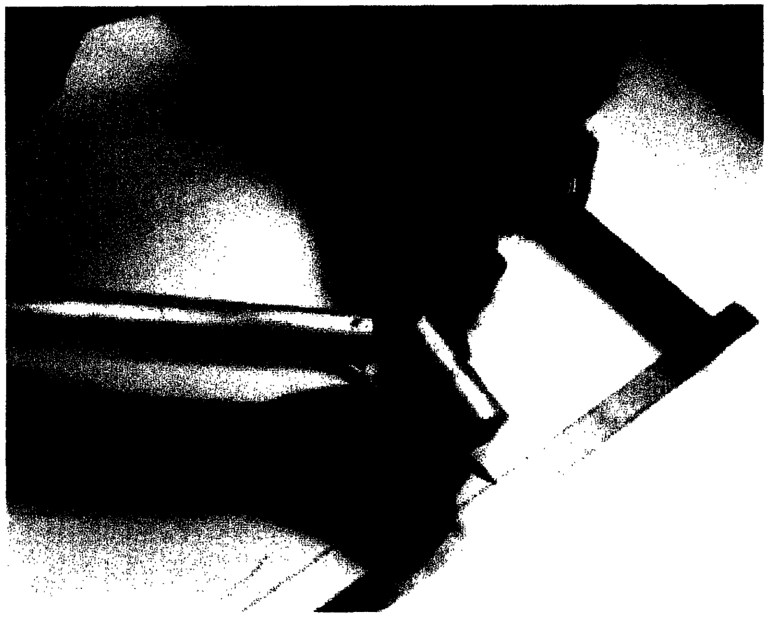

Figure 19: Rake angle being checked on the sketch.

After all the straight lengths were double checked, it was necessary to machine the fish-mouth joints at the intersection points between the various tube lengths. In order to ensure the joints were flush and accurate, some error was allowed when selecting the straight length of tube for each segment since the actual length of the finished part was defined by the deepest point in the rounded cut at the ends. Using a one inch end mill, the tubes were fixed at the required angle in the mill clamp using a level and angle blocks. After the machining of each tube, it was placed on the full size sketch.

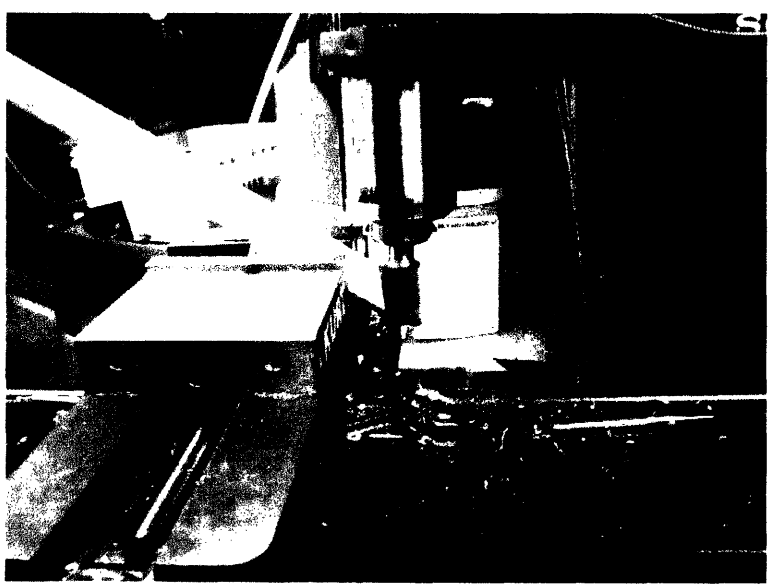

Figure 20: Machining a fish-mouth joint using angle blocks.

Figure 21: Completed joint on one of the down tubes.

Once the main external tubes were completed they were once again arranged on the paper template to verify that the circular joints were accurate as shown in figure 22. It was then necessary to cut the top tube to accommodate the seat tube. The joints between the top tube and the seat tube occurred at the same angle that we see between the seat tube and a vertical line drawn from the bottom bracket. Knowing this, the top tube was cut at the point where the seat tube would intersect and given fish mouth joints at each end. Figure 23 shows the completed frame after being sent to the MIT machine shop for welding.

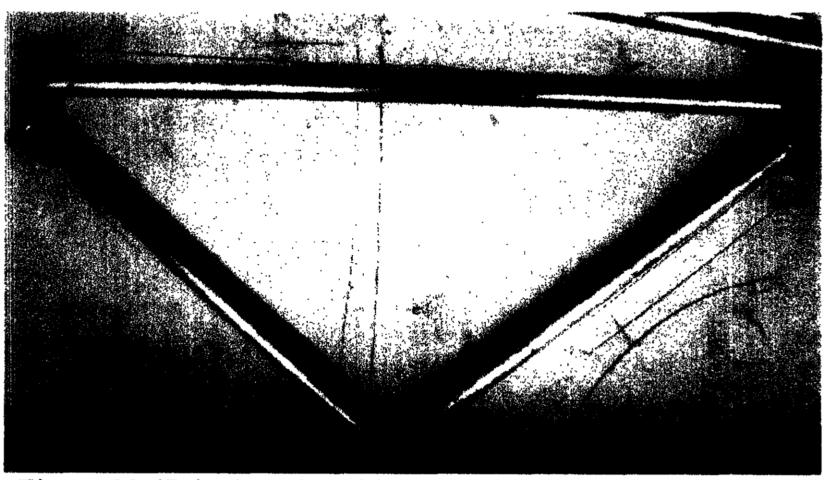

Figure 22: Tube lengths laid out on template after machining.

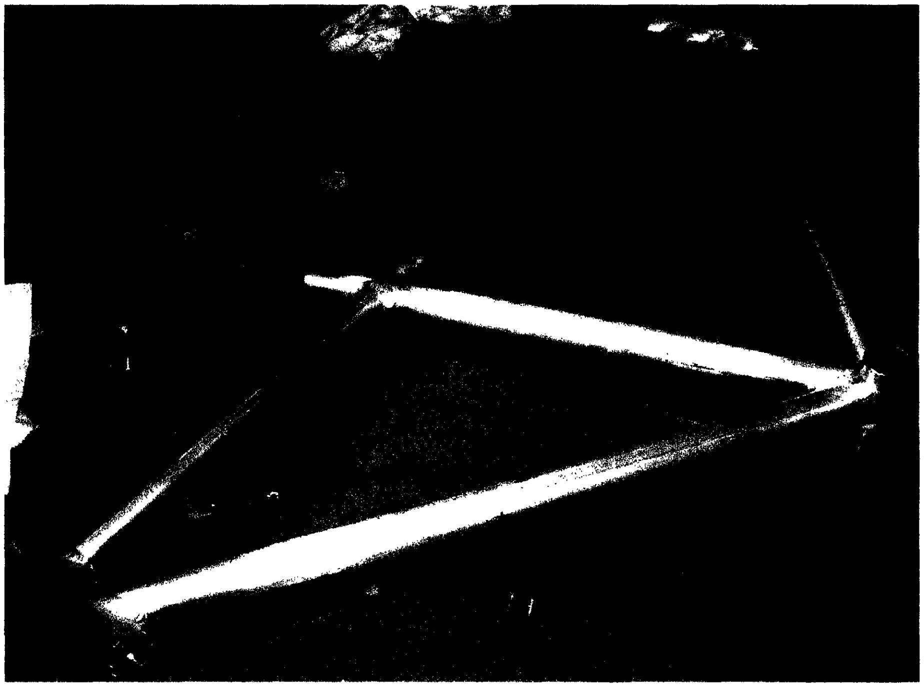

Figure 23: Frame after welding process.

As the frame was being welded we turned our attention to constructing the extendable cargo arms. These were made from 1/8" aluminum sheet bent into a square U using a sheet bending machine. The three separate pieces of the steering arms were progressively narrower so that they would fold within each other when stored as can be seen in figure 25. The dimensions of the outermost segment were 1" x 1" x 24". At 24" inches in length, the armature could be stored along the down tubes of the bike which measured in at around 26".

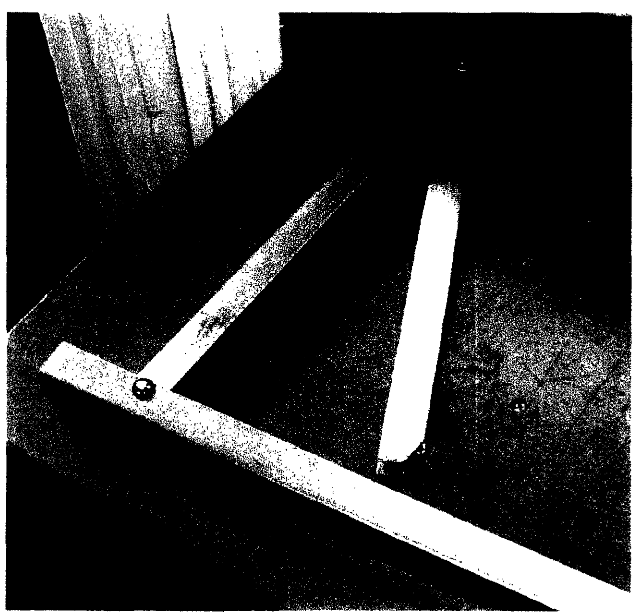

Figure 24: Retractable steering arms.

Figure 25: Steering arms retracted in storage position.

In order to provide proper rotation of each part, nylon bushings were used on the axle between each segment. In order for the arms to withstand the loads transmitted across it in the fully open position with a loaded cargo area, the overhang necessary past each point of rotation was overestimated. Figure 26 shows one of the joints in its fully extended and locked position.

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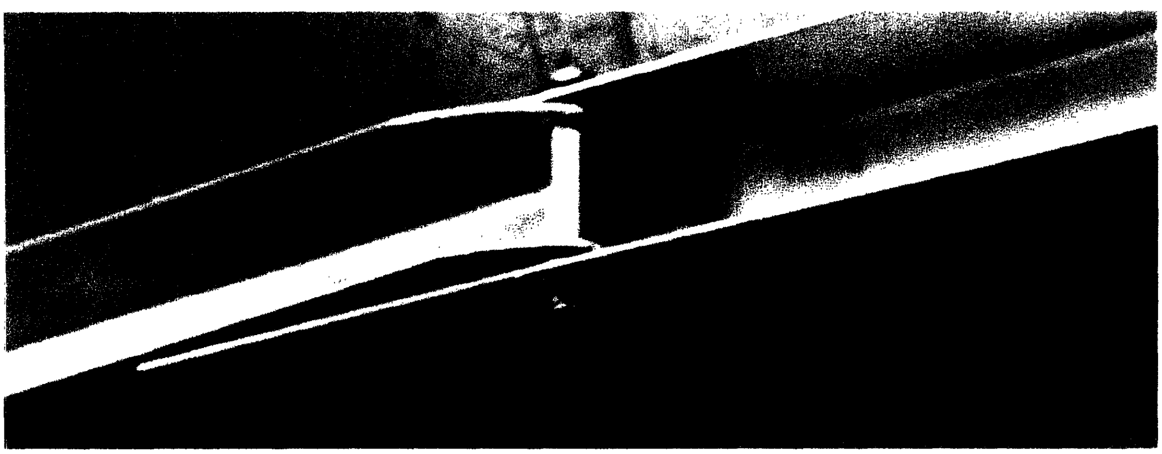

Figure 26: Joint between segments of a steering arm (note the generous overhang).

With the frame and arms completed, it was then necessary to acquire all the existing bicycle parts that would be necessary for a finished prototype. As seen in figure 27 below, these included the crank set, pedals, extra long chain, handlebar, bottom bracket, headsets for both front and rear forks, and the forks themselves. The most critical of these components were the two forks that required some machining in order to accommodate the locking mechanism I had designed. After evaluating various fork designs, the forks chosen where Instigator models by Surly. These forks were chosen not only for the robust design and construction needed to withstand loads in the directions seen in cargo mode but also due to the fact that the rear fork had to accommodate the gear that would drive the rear wheel. Due to this a wide gap between the fork legs was required and the Instigator proved to be the widest fork we could find that was also strong enough to withstand heavy use. Given the intended use of our device I found that using parts intended for mountain bikes provided the functionality desired.

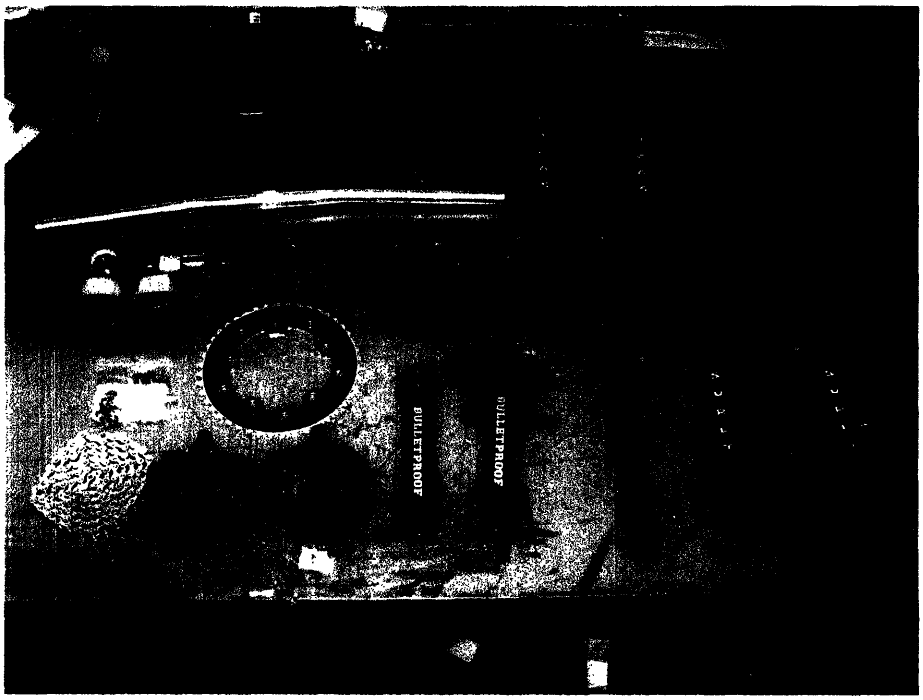

Figure 27: Purchased bicycle parts.

After acquiring the forks, construction of the locking mechanisms could begin. The machining of the slots in the forks and head tubes proved to be one the most challenging manufacturing steps in process of building the prototype. In order for the bicycle configuration to work properly the rear wheel had to lock in the plane of the frame with considerably small error. If any error was allowed, the rear wheel would not drive true when the chain was engaged. Furthermore, when in cargo mode, the alignment of both forks was important since any misalignment would lead to unwanted camber in the wheels. Therefore the utmost care was taken when measuring and machining the slots in the purchased forks and custom head tubes. A level affixed to the work table was used to ensure that that all markings and center punches were as precise as possible.

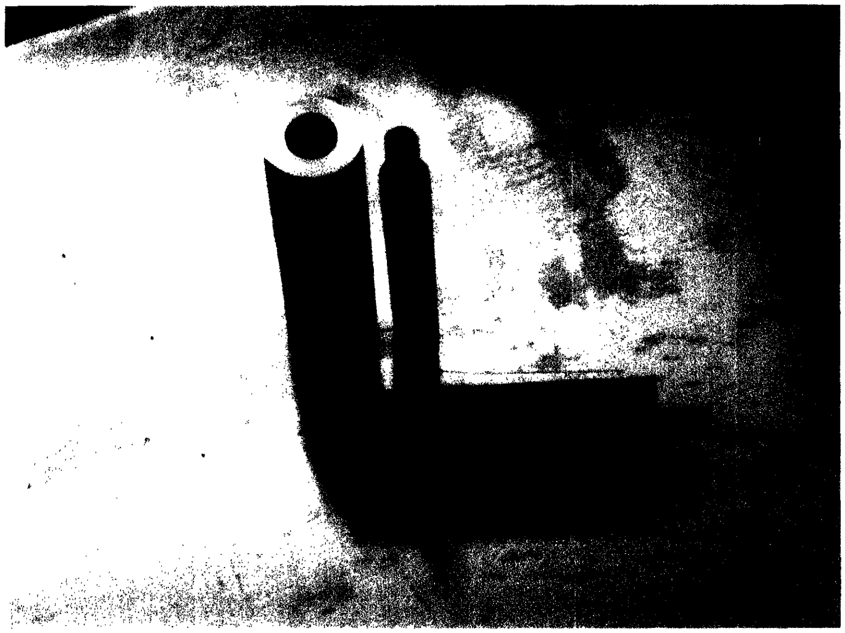

Figure 28: Pins and housings for locking mechanism.

After slotting the forks and head tubes, the pins and housing that would act as the deadbolt mechanism were machined. In order to provide a positive lock, the pins were tapped and drilled to accommodate for a locking bar and the housings were welded to the top bar as seen in figure 29 below.

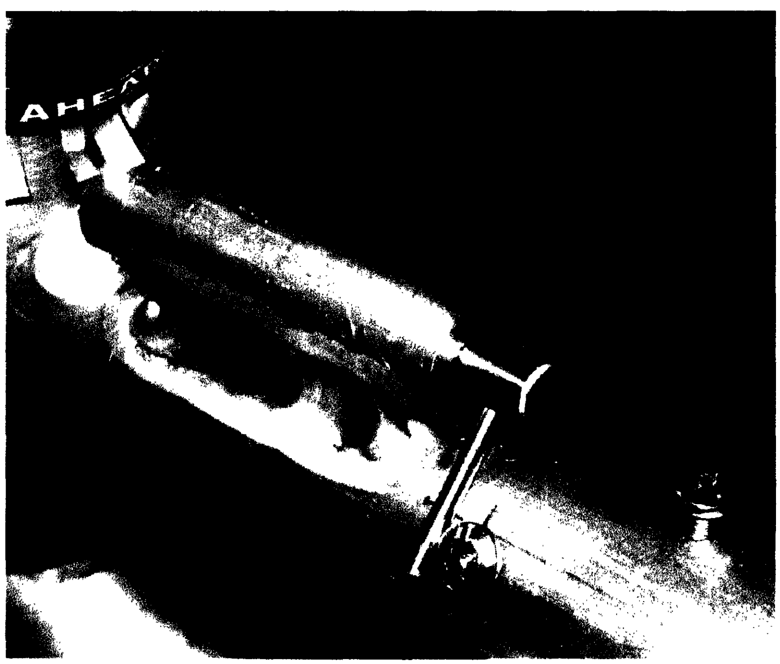

Figure 29: Completed locking mechanism.

With the completion of the locking mechanism we had all the parts necessary to complete the final assembly. The retractable arms were affixed to the frame with bushing assemblies at holes that been drilled into the frame. The head sets and bottom bracket were installed and the removable chain was tested. In the next section I will show images of the conversion process of the final prototype.

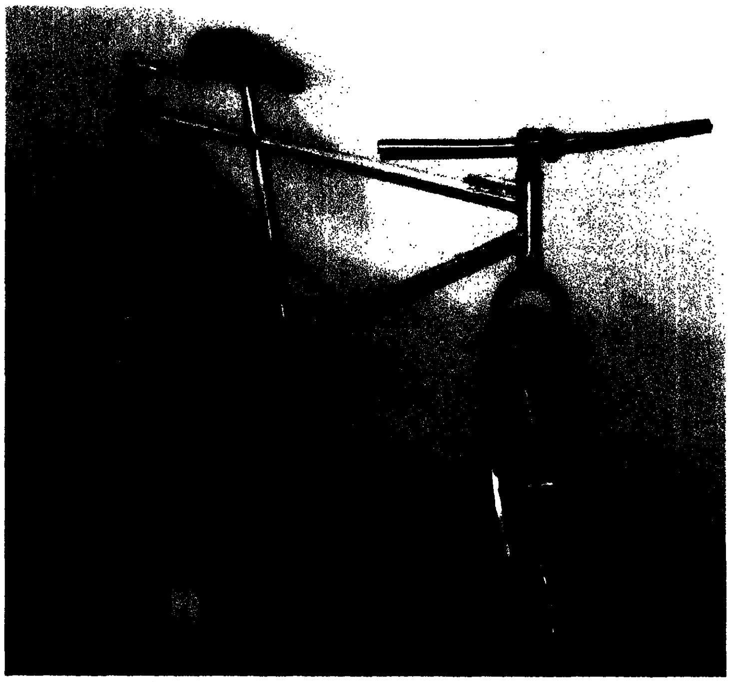

Figure 30: The completed prototype.

Figure 31: Alternate view of prototype in bicycle mode.

5.0 Finished prototype conversion process

Figure 32: Bicycle configuration.

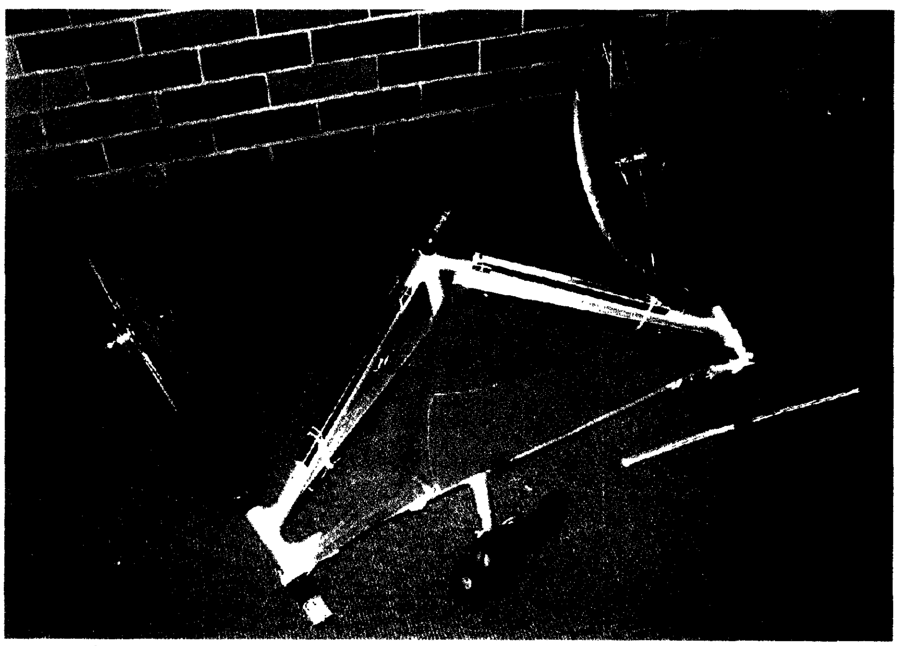

Figure 33: Both wheels locked perpendicular to the frame.

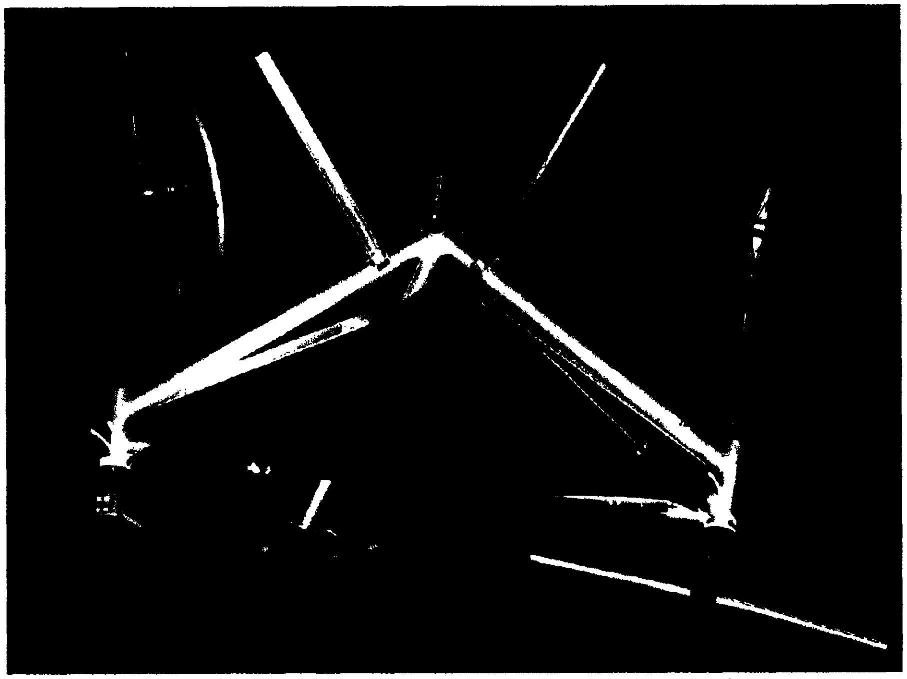

Figure 34: Cargo arms rotated and extended.

Figure 35: Cargo floor unfolded and fixed to arms.

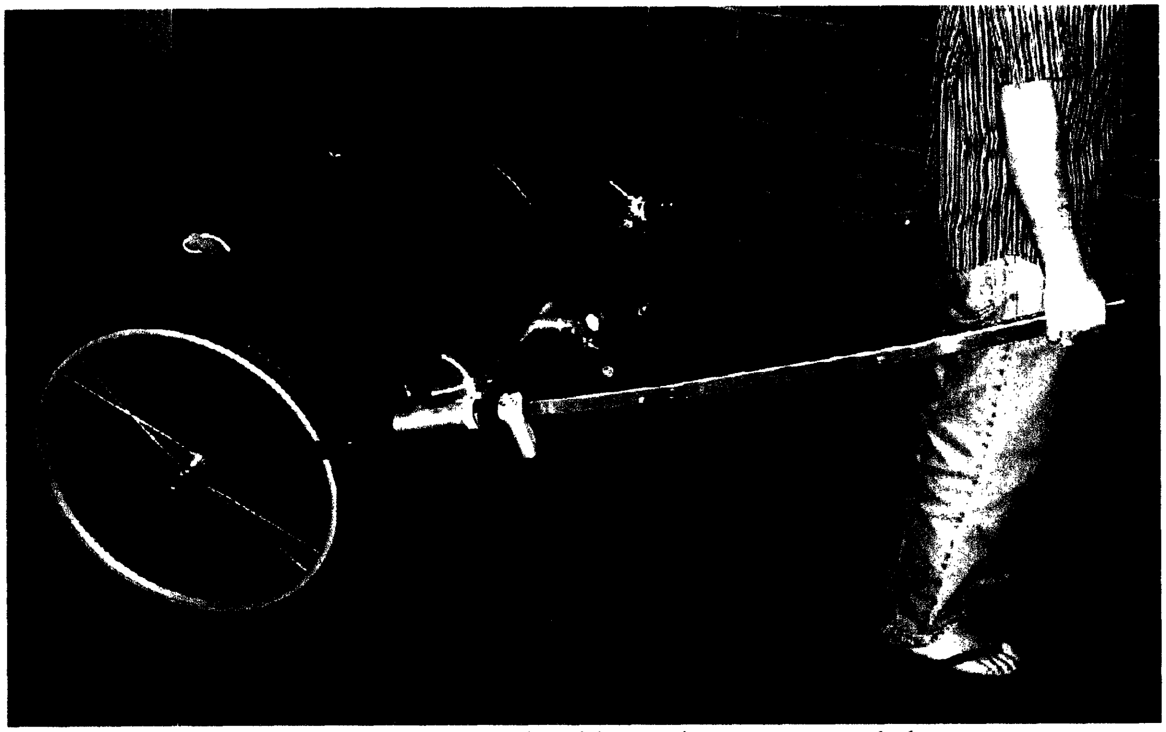

Figure 36: Cargo mode with steering arms extended.

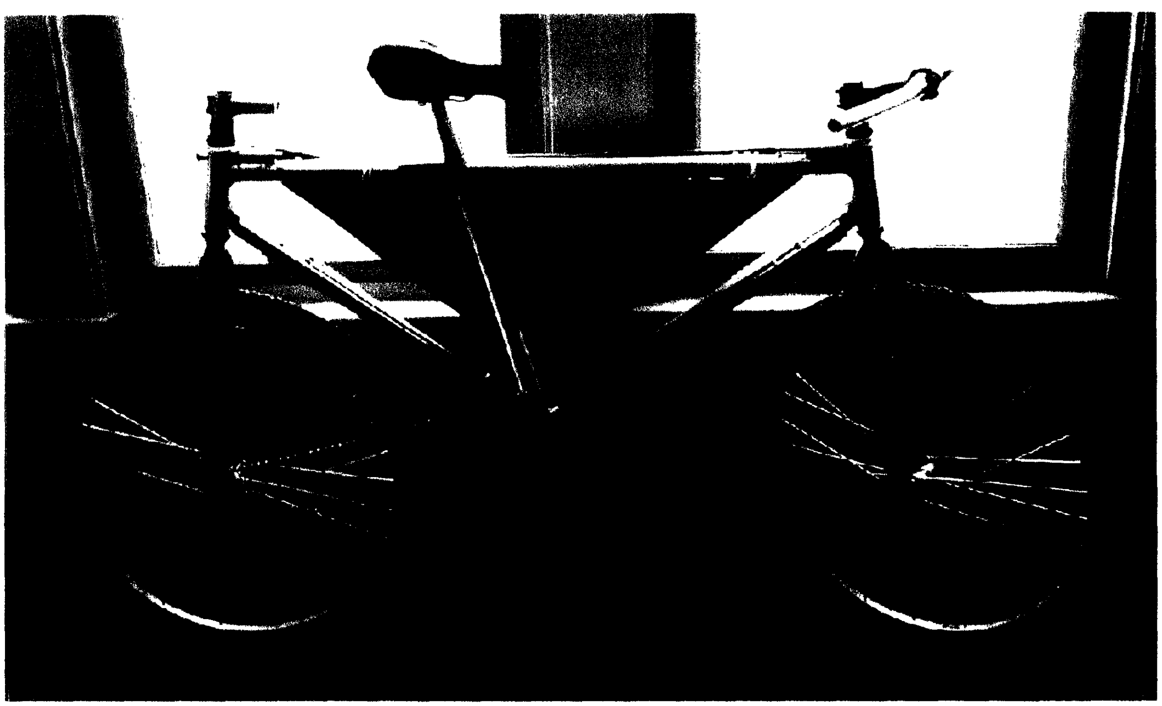

Figure 37: Fully assembled prototype in bicycle mode, alternate view.

6.0 Conclusion

Given the successful testing of our prototype it is our conclusion that the hybrid bicycle design presents an elegant innovation in human powered transportation. With its ability to carry personnel in a quick and low cost package and the added capability of being able to reconfigure for large payloads, we find a two wheeled vehicle capable of serving as both a bicycle and cargo carrier could be an indispensable tool. Among the many applications we envisioned for such a device would be its use among the ranks of the modern military. Given that the cargo area was designed to accommodate an adult individual, the design allows for extraction of wounded soldiers in situations were only multiple medics carrying a stretcher would traditionally be able to perform the task. This functionality could prove indispensable in any search and rescue profession. Nevertheless its applications are of course not limited to military use as the ability of a bicycle to take you to a location and return loaded with cargo could be used by many individuals in every day life. In developing nations especially, where the bicycle is often the most common form of transportation, a design such as this that improves a familiar technology by adding functionality while maintaining compatibility with existing bicycle parts and maintenance procedures would indeed be a welcome addition.

7.0 Further Research and Suggested Improvements

Even though the concept proved to be valid through the design process and prototype construction, there were various design details that required special attention and merit further development. In particular, issues with manufacturing precision in the locking mechanism of the forks presented challenges during prototype construction. Since the deadbolt assembly and the slots through which it would pass would dictate the orientation of the wheels when in locked positions, their alignment was a critical manufacturing step. In the process of welding, the deadbolt housings were attached with a slight angle of error which resulted in negative camber for both wheels when in cargo mode. Further research into a manufacturing process suitable for constructing the locking mechanism on a large scale would be justified.

Additionally, during the testing of our prototype we came to envision possible design changes that would further improve the driving dynamics of the vehicle while in cargo mode. The head tubes of our bicycle design were given a 10 degree rake angle, less than a common bicycle, in order to ensure that the bicycle mode retained the effects of precession that give the bike its "self-driving" effect while minimizing the effects of toe while in cargo configuration. After testing the prototype we found that 10 degrees was still too large an angle and toe-in became a problem for the cargo mode's rolling dynamics. Therefore a future revision of this design could reduce the toe by giving the head tubes a more vertical profile while replacing the straight forks with ones designed to angle forward at a point past the straight head tubes. In this way the bicycle would retain its drivability and the toe-in problem could be eliminated.