Human-Robot Interactive Parts-Cart for Automotive Manufacturing

A final recommendation report

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Preface

The automotive industry has many line workers that assemble the parts of a particular vehicle component at a station. The purpose of this report is to outline the design and recommended construction of a parts-cart that is capable of mounting a robotic arm to assist with selection of the parts. The current state of the automotive line is such that each worker remains stationed for a full shift at a specific stage of production and has their own supply of the parts that they use for multiple cars. The focus of this project has been to develop a parts-cart for use with the assembly of a car door as a proof of concept.

Currently, a car door moves along the assembly line and multiple workers must configure their designated components quickly and accurately. This method puts stress on the workers who must find and assemble parts in as short a time as 5 seconds per part; this can lead to errors that slow the entire process down. Any errors that result in the particular component of the car get pulled off the production line.

Another major issue with this style of production is that it limits production capacity at any manufacturing plant to just one car model. Workers only have the parts necessary for a single model and changing the production model requires retraining and restocking of new parts.

By having a parts-cart capable of following the car door as it proceeds around the production line allows production workers to have access to only the parts necessary to that particular model. By reducing the responsibility of the worker to only receiving the necessary parts rather than handling and sorting, there is a reduced possibility for error. More importantly, since all of the parts sorting and managing occurs with the parts-cart, changing the bins for one model of car to another becomes easier.

Executive Summary

The robotic/human interactive parts-cart was designed and built as a proof of concept test bed for the CARIS Lab with application to the automotive industry. The purpose is to design a parts-cart capable of testing and demonstrating the effective and efficient handling of parts by a robotic arm or human. While few solutions exist, they are expensive and require an overhaul of production processes in the automotive industry.

The scope of this project is limited to the design and fabrication of the parts-cart, while keeping in mind design requirements set forth by the robotic arm (WAM) and general safety for humans. The project design requirements are such that the fully configurable parts-cart must be capable of mounting a robotic arm for accessing parts in bins or pallets. The bins must be strong enough to hold 20 LBS worth of various parts, and pallets must be simple and easy to maneuver by the robot.

The structure of the cart was chosen to be made of CreForm piping and joints, as they offer high structural integrity and simple configurability. After the cart was built, several testing methods were used to determine the success of the objectives: Human/Robotic Accessibility, Configurability, Deflection Tests, Vibration Tests, and Maneuverability Tests.

While accessibility and maneuverability tests are qualitative in nature, they successfully provide proof that the design choices are the correct ones. The Maneuverability Test showed that the cart was able to handle extreme cases where the cart was required to go over large bumps or turn on extreme angles. The cart was also noted to be easily customizable with regards to bin and pallet sizes, and even overall dimension sizes. Since the cart was required to fit through doorways, CreForm piping made it easy to alter the overall width.

The Deflection and Vibration Tests offered quantitative results for the parts-cart. Weight was applied to key stress points, and the maximum deflection was measured in the vertical and axial directions separately. It was determined that even with as much weight as 95 lbs; the vertical deflection was only 4 mm. The axial deflection, however, was noted to be much larger (5 cm) due to the lack of structural support between the bin shelving and robotic arm mount. Vibration tests

were also applied in SolidWorks and determined to be minimal for the small forces expected for the cart. In a 0.5 kN test with vibrations at resonance, the largest transverse axis deflection was 20 cm.

In conclusion, the parts-cart, designed and built, follows all project objectives accordingly. Overall, the design is effective and meets the design requirements for both human and robotic control. It is capable of being maneuvered by humans and robotics and can traverse ground obstacles that are 2” (no more than 3”) and under. It is recommended that an I-beam support structure and aluminum (or metal) plate be added to the base of the cart to handle the axial deflection under load. It is also recommended that the length of the cart be shortened for the purposes of its applications in the CARIS Lab.

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1.0 Introduction

1.1 Background and Significance

The recommendations described in this report have arisen for the project to build a proof of concept robotic parts-cart. The project is part of a larger project to implement robotic parts control systems and robotic-human interaction in automotive factories. The design of the parts-cart is intended to facilitate the interaction and decrease the number of errors that cost time on the line. Similar systems exist only in a few factories around the world and are usually only designed to deliver parts with the car but do not include robotic arms that can pass the parts to the worker in the proper order. One similar system exists in the 'transparent factory' that Volkswagen operates in Dresden, Germany. The robots in this factory carry all of the parts necessary for a single vehicle along the line with that vehicle (Volkswagen Car Company, 2012). The main difference with this project is the reduction of the cost of the system through the use of smaller, modifiable designs with reduced robotic components, as well as the robotic arm that will simplify the access of parts.

1.2 Project Objectives

The following is a brief summary of objectives outlined in the proposal, and applied as a guideline for the project. The objectives have been chosen in order to conform to design specifications of the parts-cart.

1) Deliver a cart structure that supports the robotic arm, even if it is moving through its full range of motion, without loss of stability. For this iteration, the arm will be the WAM robotic arm. *[By April 2012]*
2) Supply (source) bins that are strong enough to contain 20 lbs weights without distortion and come in standardized sizes that will fit on the cart. *[By January 2012]*
3) Supply (source) the structural piping, joints and base such that the construction is customizable, simple to build and scalable to larger designs if necessary. *[By January 2012]*
4) Establish whether pallets are the optimal solution for handling and hand-off of parts of irregular shape / large size / consistency (i.e. window seals or door-lock mechanism). *[By April 2012]*

1.3 Scope and Limitations

The goal of the project is to design and build a parts-cart as a test-bed for the CARIS Lab. The purpose for this project is to provide a method of designing a practical interface for the WAM robotic arm in order to demonstrate the effectiveness of parts hand-off and other human/robotic interactions. As such, the scope of this project is limited to building the parts-cart. To be clear, the project only involves structural design while maintaining practicality, customizability, scalability as well as general safety. The project does not consider software or robotic design, but considers their limitations with real-world application of the parts-cart.

1.4 Report Organization

The following recommendation report provides an analysis of the chosen parts-cart design as well as the approach taken in building it. The report describes the tests done to determine the limitations of the parts-cart with regards to deflection, pipe bending, vibration and maneuverability and their corresponding results.

2.0 Discussion

2.1 Design Methods and Resources

The designs for the parts-cart were developed as a collaborative process with project sponsor, Dr. Chris Parker. There were multiple design iterations that were considered prior to the final proposed model but were filtered out due to various design considerations. Upon selecting the final design to use for production, the model was formed in SolidWorks to allow for simulated testing and analysis.

The decision to purchase the CreForm was made because their products make altering the design easier to do on an as-needed basis. One added benefit is the years of experience that the associates at CreForm Ltd have in designing similar cart structure for other industries. These carts do not have the restrictions required for the inclusion of a robotic arm; however, consultation led to the addition of two casters in the middle of the frame that increased the stability and strength of the cart.

Sourcing products from supply companies developed much of the design, even if they were not purchased in the end. Some of the components, such as parts bins, were readily available from many sources but were not purchased for the design model. Instead, similar bins to the ones sourced were used due to their accessibility in the project lab. The rail systems are also commercially available from multiple sources; however, due to timeline and cost constraints, a modified aluminum 8020 extrusion system was used as a substitute. In an industrial setting, it is likely that the corporation would have dedicated suppliers that can provide the necessary materials at a discounted rate.

Other useful resources in the design process include a collection of videos outlining the process of manufacturing a vehicle on an assembly line (Holden Automotive, 2011). This allowed the design to be properly tailored for the automotive industry without having to visit a production plant during the design period.

2.2 Testing Considerations

In producing the final cart design, it was necessary to come up with tests to gauge the relative success of a given model. There were five main tests used to determine feasibility of the design and only by passing all of the tests was the final design deemed fit as a parts-cart. Below is a discussion of the tests and their implications; the results of the tests are discussed later in section 2.3 Results.

Human / Robot Accessibility

The majority of the ideas that were discussed in the design process were discarded because of considerations due to the necessary accessibility restrictions. Any parts on the cart must be available to the robot arm at all times, however they also need to be available to a human worker in the event of failure or shutdown of the robotic system. The restrictions on the movement of the robotic arm, and the elbows and joints that are part of the arm, give a maximum and minimum range for the location of the parts.

Accessibility also limits the style of parts container used on the cart. Bins with open tops are easily accessible to either humans or robots, however many of the parts that go into a car do not lend themselves to easy manipulation by robotic manipulators. Pallets designed as a secondary parts container system allow for the handling of soft, flexible or awkwardly shaped parts.

Robotic arms do not lift in the same manner as humans generally and the pallets are designed with this difference in mind. A handle placed underneath the back of the pallet allows the arm to grab the pallet and lift, with most of the weight of the palette supported by the forearm of the robot. The feet of the pallet should, ideally, be self-setting, to reduce the necessary accuracy of the robot in placing the pallet back into place. Three designs were conceived that would accomplish this goal; cone pegs, sloped bars and sloped bearing rails. The cone peg and the mounting plate designs can be seen in Appendix A and are functional on the cart. The sloped bearing rail pallets were not completed, as they required extra time to order in the necessary parts. See section 2.5 alternative considerations for a more detailed description of this alternate solution to a pallet system.

Reconfigurability

One of the major benefits of the parts-cart system is the reconfigurability of the design to meet the current production needs. Initially, reconfigurability was taken as the ability of the cart to be reshaped to match the quantity and size of parts that it would need to carry. After further consultation, reconfiguring was reduced to changing the size and quantity of the bins and/or pallets that would be used on the cart frame. The change in direction is due to the likelihood that companies will purchase welded steel frames rather than modular tubing solutions for use in factory applications. Reconfigurability of the bins and/or pallets means that there should be no specifically constructed bins but rather a bin system that will withstand the strains of use and still be easily moved.

Deflection Testing

To ensure that the cart is structurally capable of sustaining the forces and torques placed on it by the parts and robot arm, the amount of deflection under loads needs to be quantified. In this testing, the constructed design was placed under a 'worst-case' scenario for weight distribution and the amount of deflection was measured.

The vertical deflection under load shows the strength of the design and tubing. For this test the maximum estimated loading of 50 lbs was assumed, based on discussions with sponsor and analysis of the components of car door available at the CARIS lab, and maximum load tested was 95 lbs at a single point that was the furthest point from support. The parts were loaded individually into one of the bins that would normally be used to house the parts and deflection from original position was measured. The loading was left for a 24-hour period after test completion to determine the amount of deformation over time as well.

Angular deflection is also critical to the design and is used as a measure of the structure's resistance to torque and bending moments. The angular deflection was tested by applying force perpendicular to the support structure at the top of the shelf; the amount of deflection was measured from the original, vertical alignment of the bars.

Vibration Testing

Vibration studies are necessary for environments where there are periodic forces being applied. When forces are applied in a periodic fashion, structures may reach resonance at specific natural frequencies, leading to oscillations of a much larger magnitude than otherwise. At these frequencies, the transfer of energy from the external source occurs in phase with the exchange of energy from spring potential to kinetic. The motion is amplified and the energy received by the structure is converted directly to kinetic energy rather than spring potential energy; hence the significant displacements. This can be quite damaging to machinery and can lead to catastrophic failure of joints. One well-known example of failure caused by resonant vibration is the Tacoma Narrows Bridge, which oscillated at its natural frequency because of the wind. Thus, designs with potential periodic vibrations should be tested to find their natural frequency and corresponding harmonics.

SolidWorks provides a simple method to analyze structures and solve for such information. The simulation provides a list of the 5 most significant frequency responses, which correspond to the natural frequency and 3 harmonics. This information can be used in 3 main ways. The first is to attempt to safeguard the design from vibrations of those frequencies. Changing motor RPMs or compressors rates can do this. The second is to change the natural frequency of the system by adding damping, such as isolators for motors or isolation mounts for floor-mounted equipment. The third is to fundamentally change the system by modifying the mass of the design or changing the geometry.

For this project, the resonant frequencies are in a range, which will not occur, in regular operation. When a motor is added to the robot drive-axis, an isolation mount may be created if the motor must run at a resonant frequency. However, it is unlikely that this would be necessary.

Maneuverability testing

As the final design is intended for use in a factory setting, it is necessary that the cart be able to maneuver around/over obstacles as it follows the component around the assembly line. To this end, experiments were specially devised for determining the overall maneuverability of the cart and the ease with which it can be pulled around the factory.

The first test is to have the parts-cart pulled around by a human operator and sees what the smallest radius of turn the cart can maintain at a given speed. While turns on the assembly line are generally not sharp radius 90-degree angles, ideally the cart should be maneuverable enough to avoid shelves and people in the stocking area. The analog used in this test was a straight hallway with multiple obstacles and people lining the sides as well as a 90-degree corner. The speed of the cart will also play a role in the effectiveness of this test and, since there is not enough data on the speed, this test is more qualitative in nature.

Next, the cart was to be maneuvered by the PR2 Human Analogue Robot available to the CARIS lab.

While the initial intention is to have the cart towed by the overhead crane system available in an automotive factory, later iterations may need to be organized and stocked by humans and/or robots. As such it is important that the cart is maneuverable by both humans and robots. The PR2 is an anthropomorphic robot capable of grasping handles similar to humans and applying forces and torques on the handle while moving (Willow Garage , 2012). This test differs from the human only test because of the added challenge of simplifying movements that turn the cart such that there is less difficulty for a robot to understand the necessary movements to produce the desired motion. Caster choices are affected by this test because locked casters do not behave the same as swivel casters under torque motions. The cart must also not be completely uncontrolled as it is moved either, as this may be a safety risk or result in damage to the machinery and robots.

In the factory setting, the cart will be towed around the floor by the same overhead crane system that is moving the component. The overhead crane present in the extracurricular lab in Hennings will be used to simulate the towing crane that would be seen on the assembly line. The outer radius of the corner that the cart sweeps out as it moves will be recorded and ideally will not exceed the furthest distance between two points on the cart by more than 5% at any given point. If the outer radius is much more than this length, it is an indication that the parts-cart is not under control throughout the entire motion and the caster system and/or towing system may need to be altered.

The final test of the maneuverability of the parts-cart is a "Bump Test". The idea of the Bump Test is designed to determine how well the cart can handle going over objects and cables that may be on the factory floor. In a normal setting, cables are covered by sloped protective covers to reduce tripping hazards. The parts-cart needs to be able to go over these covers, as well as other small obstacles.

2.3 Results

Deflection Test

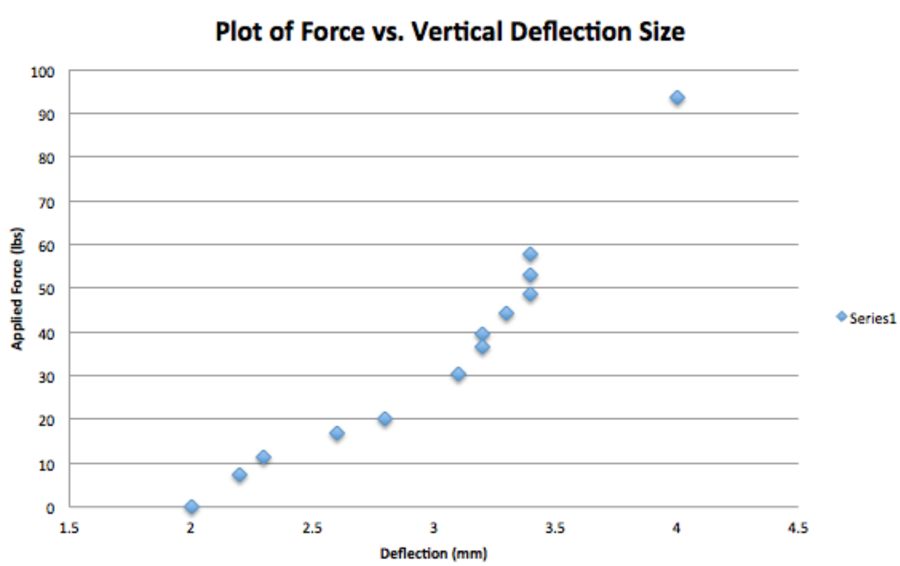


Figure 1: Force vs Vertical Deflection Size

Figure 2: Force vs Forward Deflection Size

Maneuverability Tests

The maneuverability tests were performed and recorded on video; the videos can be viewed online (Robson, 2012). The cart was able to turn a full 360 degrees around the central axis in a hallway of width 2m.

Stress Analysis Simulations

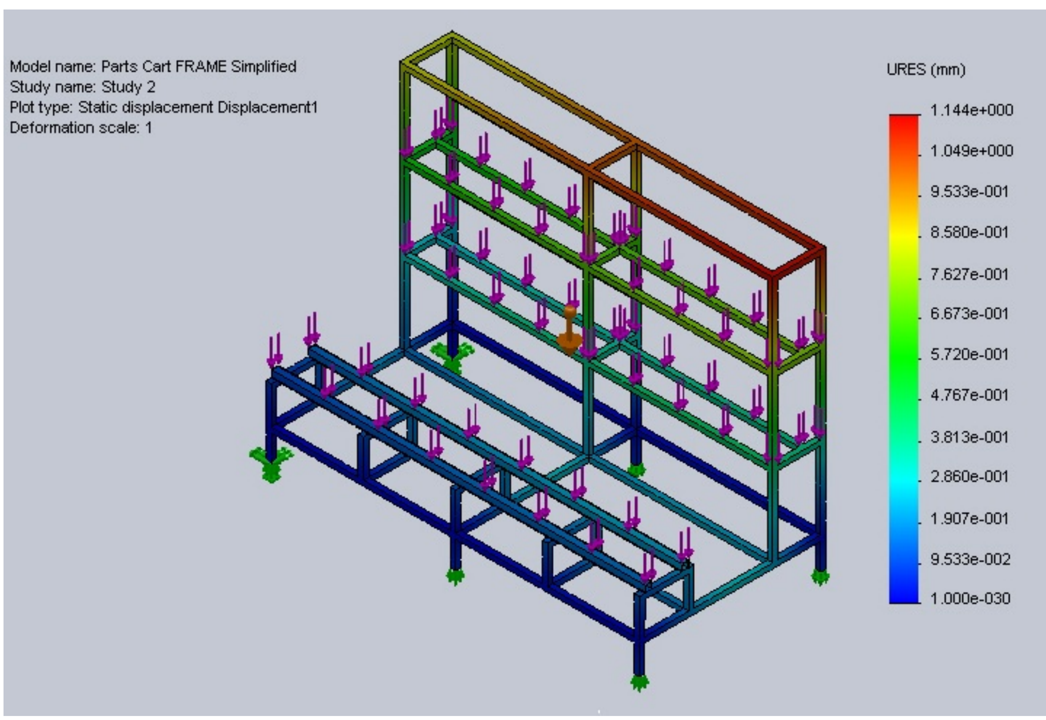


Figure 3: Stress Simulation - Deflection

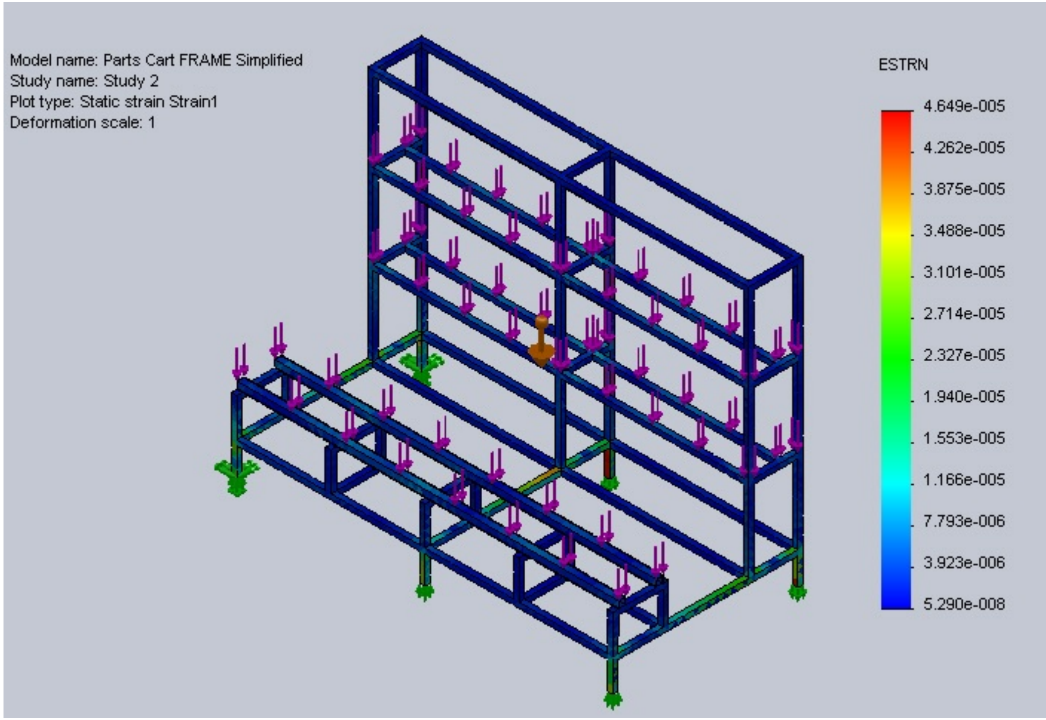


Figure 4: Stress Simulation - Strain

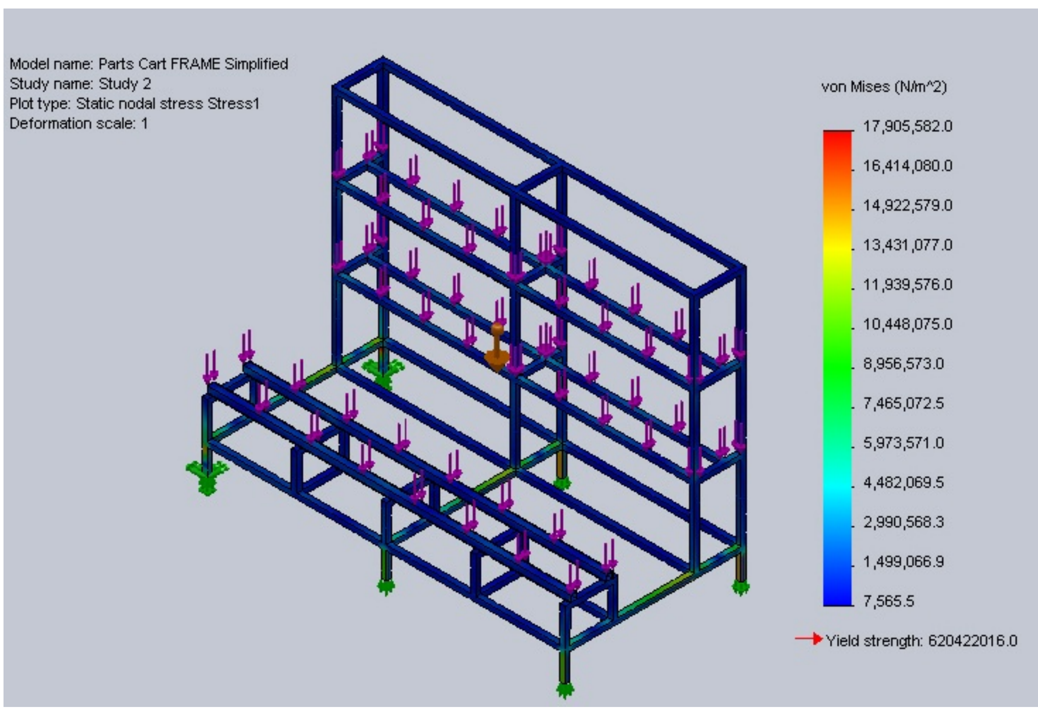


Figure 5: Stress Simulation - Von Mises Stress

Vibration Simulations

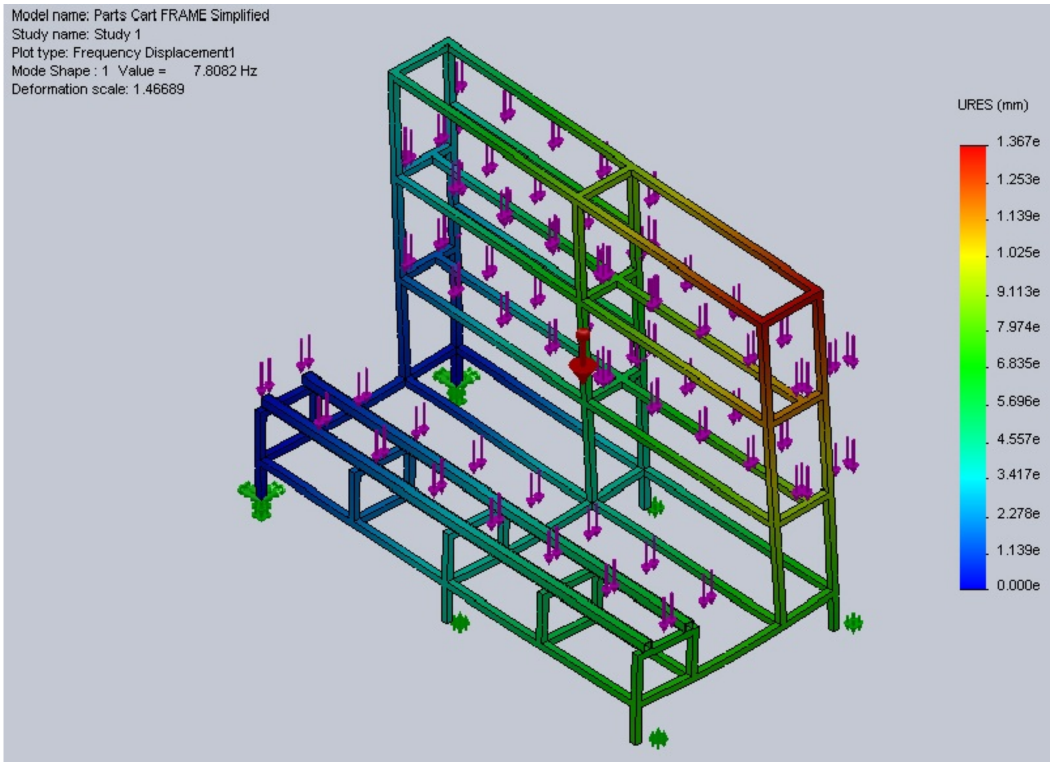


Figure 6: Resonant Vibration Simulation - Frequency 1 (7.8082 Hz)

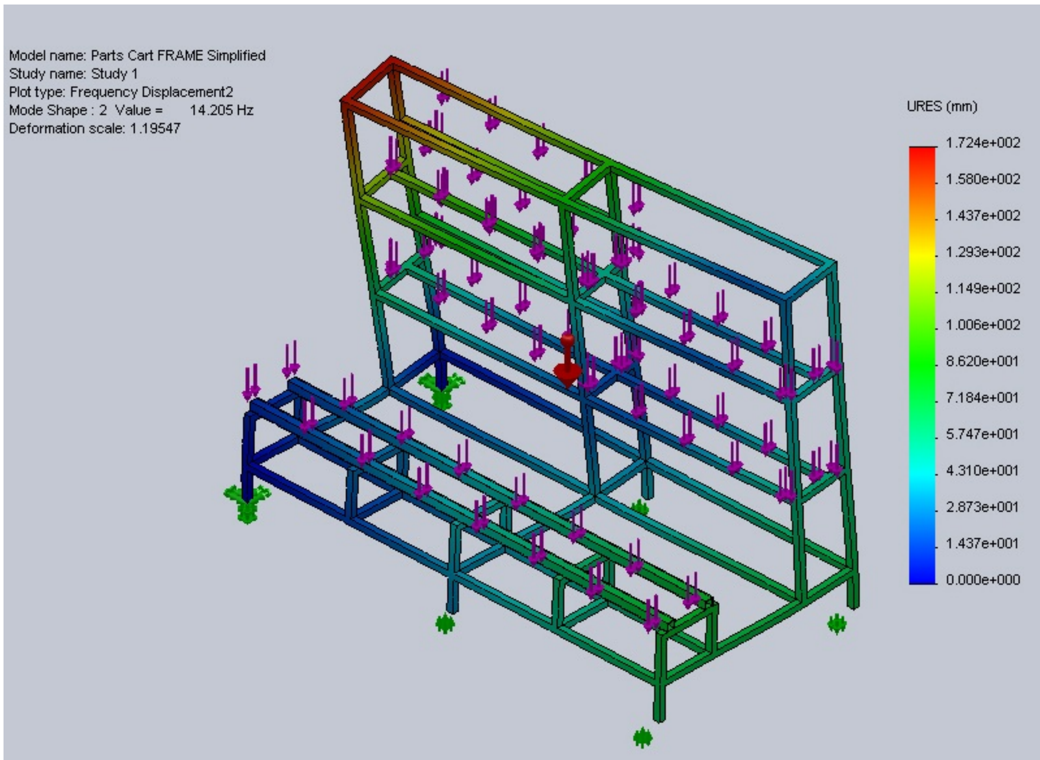


Figure 7: Resonant Vibration Simulation - Frequency 2 (14.205 Hz)

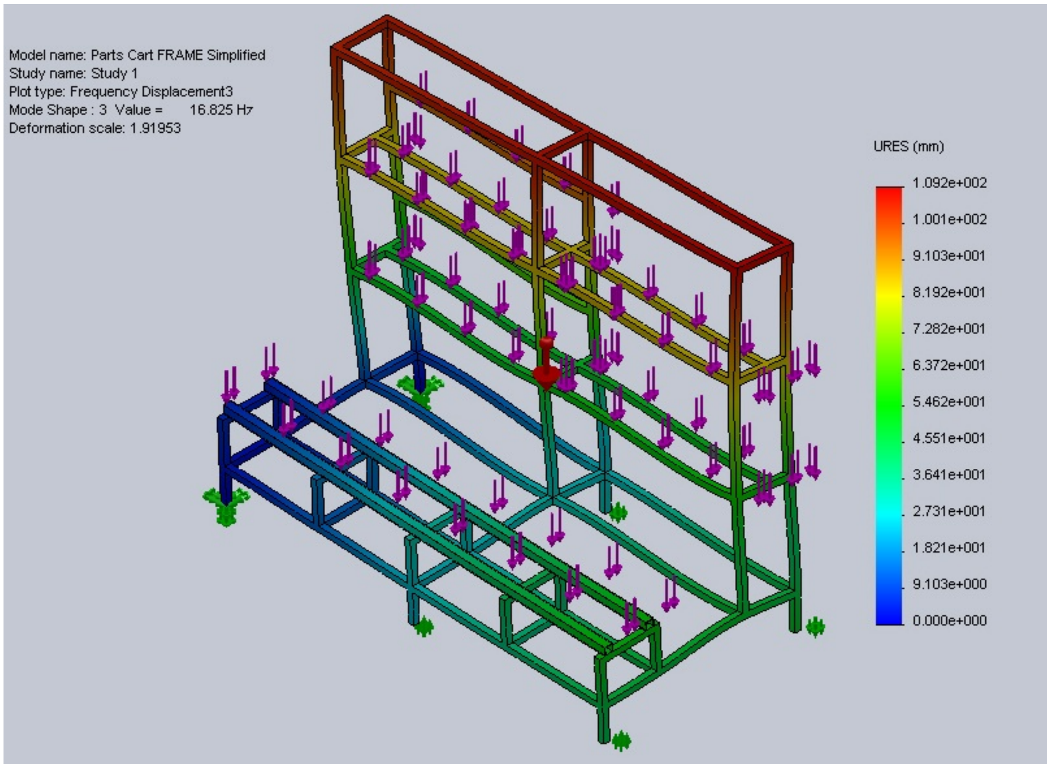


Figure 8: Resonant Vibration Simulation - Frequency 3 (16.825 Hz)

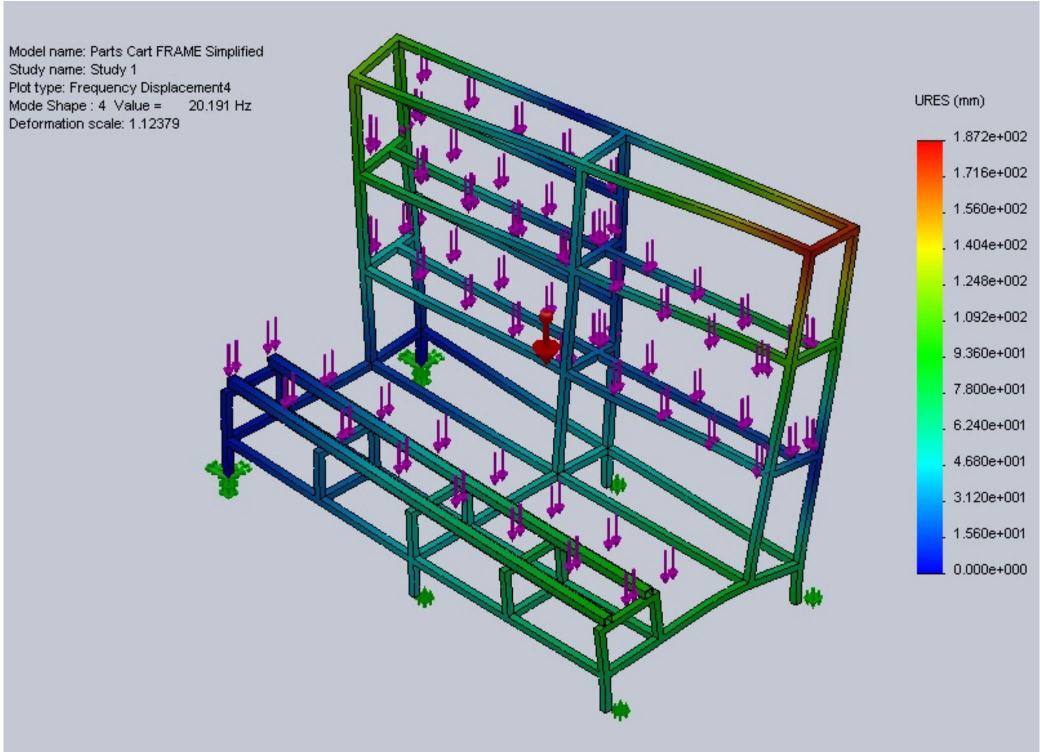


Figure 9: Resonant Vibration Simulation - Frequency 4 (20.191 Hz)

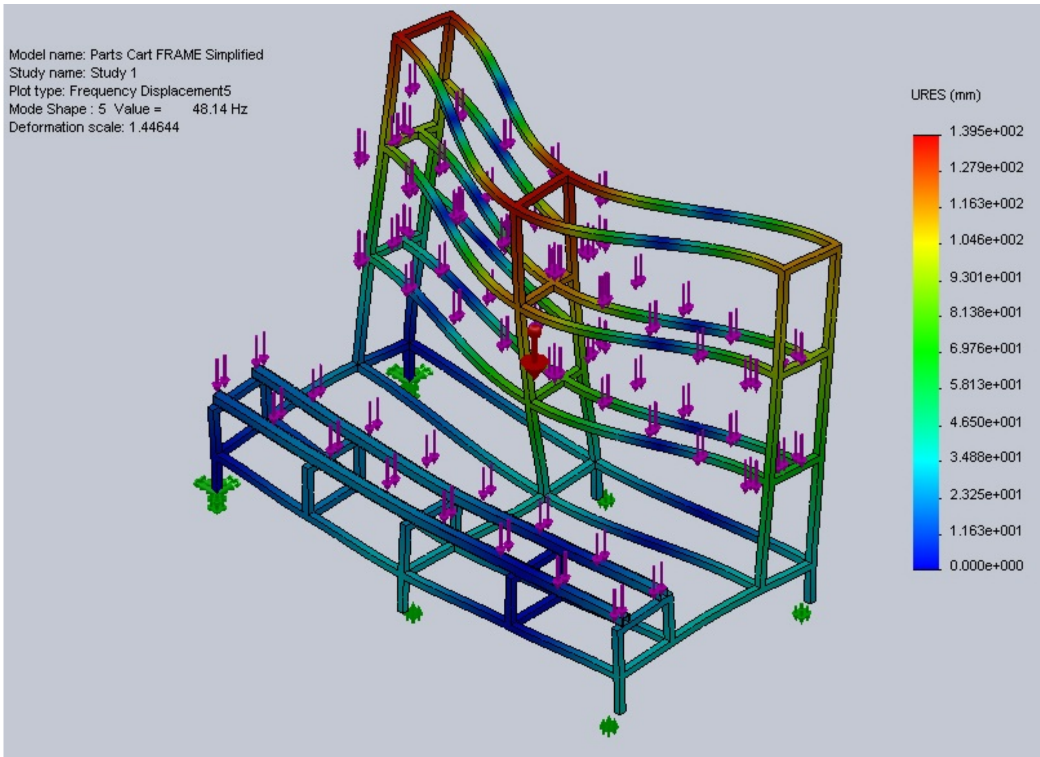


Figure 10: Resonant Vibration Simulation - Frequency 5 (48.14 Hz)

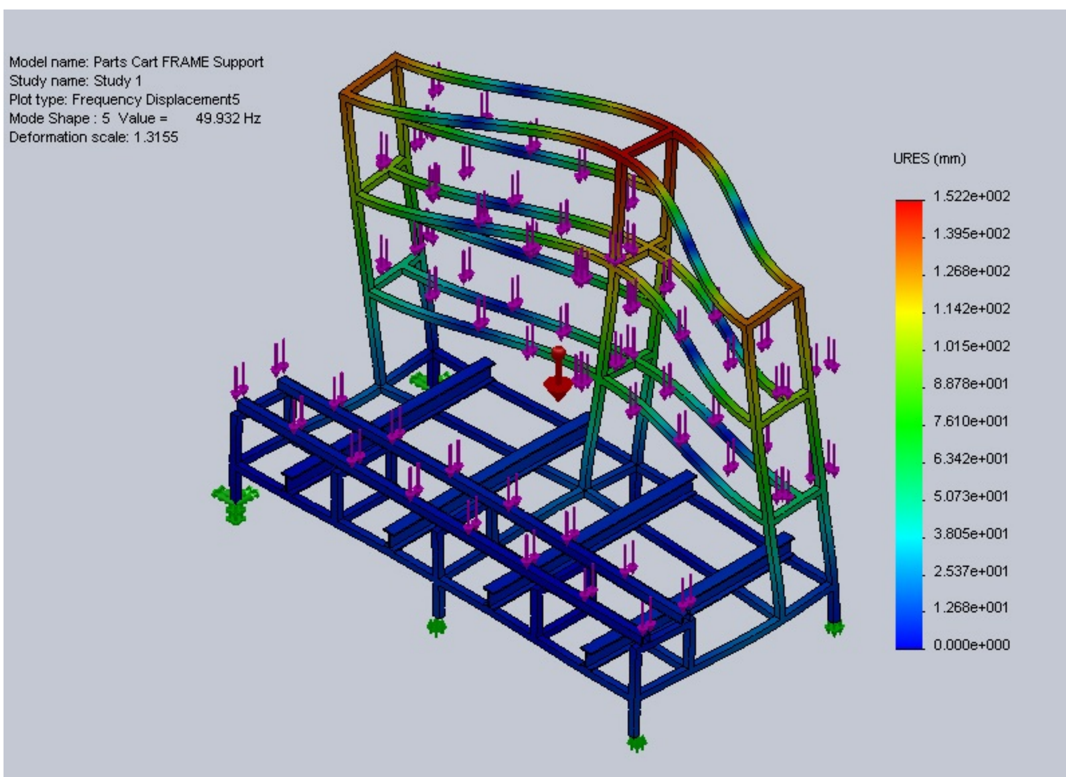


Figure 11: Modified Resonant Vibration Simulation (with I-beams) - Frequency 5 (49.93 Hz)

2.4 Discussion of Results

The results of the testing procedures show the feasibility of the cart design for use in a factory setting. Based on the vertical and angular deflection tests, the structural integrity of the frame can be determined under loadings exceeding the anticipated maximum. The maneuverability tests show the amount of stability and control that the loaded cart will have while traveling the assembly line. Vibration testing is necessary to avoid catastrophic failure due to resonant vibration. The human/robot accessibility is used to determine whether the cart will function as it is intended, the robotic arm needs to be able to access all parts and a human must also be able to do the same in the event of the robotic system failing.

Structural Integrity

Based on the plots of the vertical deflection test, the strength of the shelving system on the cart under loading is sufficient to support double the expected loading maximum. From this data, along with the 50 lbs loading capacity of 10 ⅞" x 11" Akro style bins (Akro Mils, 2011), the shelving unit will be capable of sustaining higher loads than the bins themselves can carry and the deflection in the shelf will still be small.

The results of the angular deflection testing are not as favorable. The high amounts of deflection under relatively low amounts of loading led to stopping the testing before reaching the goal of 100 lbs. A 4.8 cm deflection at the top of the cart when loaded with a horizontal force of 70 lbs shows the weakness of the crossbeam, which support leads to deformation as the torque is added to the frame and this deformation has negative effects on the rest of the structure. The weight of parts in the bins and pallets will produce similar torque to the test values on a consistent basis and without a proper system to distribute the weight properly; the robotic arm will lose alignment. As a result of the angular deflection testing, it is recommended that the I-beam frame strengthening explained in section 2.5 Alternative Considerations be added to the cart.

One additional source of deflection that could not be tested in this iteration was the deflection in the rail and frame due to the motion of the robotic arm while extended or moving. As the arm reaches to grab a part and moves to the end of the cart for hand-off, the weight of the arm will change from reaching towards the shelving to reaching away from the shelving and will travel down the length of the cart at the same time. The dynamics of this motion are hard to model and as the robotic arm is not available for testing at maximum speeds under its own control, it is not feasible to use a motion test.

Additionally, a software simulation of deflection was done to calculate for maximum operation loading. Stress, strain and deflection were analyzed with a 30 kg load from the robotic arm and a 100 kg load for parts. With the load distributed between the 4 shelves, deflections occurred on the order of 1.14 mm. These results are acceptable for direct loading of the cart; however, the model used for this simulation is a simplification of true model using square cross-section pipe with the same area moment of inertia. The results also vary from the loading test done on the cart prototype, as the physical load was concentrated on one shelf, in a single bin.

Stability and Control

Maneuvering the cart through simple obstacles and around corners proved to be quite difficult during this testing phase; turning the cart is different than it would be for a standard wagon or cart design. When turning the cart, the entire structure rotates around a vertical axis centered between the two middle, fixed casters. This method of control means that the cart does not need a large region to turn a corner and can make a 90 degree turn between two hallways that are only approximately half the longest distance between two points on the base of the cart.

Pulling the cart from an elevated position, such as an overhead crane, behaves similar to a human pulling the cart, provided the angle that the crane pulls the cart from is greater than 45 degrees from vertical. In a factory setting the cart will be pulled from the same overhead crane system that carries the automobile component through the assembly line. The presence of the component in front of the cart should require that the cart is a distance back from the crane point and this will work with the restrictions found in testing.

The cart was able to manage obstacles up to 3" in height, having a sloped side, without getting stuck or experiencing large amounts of stress in the handle. Obstacles larger than 3" will cause more issues with the height of the base of the frame and would require a modification of the size of the casters. The biggest concerns in the factory setting are dropped parts, of variable size but generally bolts or equivalent size objects are most common, and cables. The cables and the protective covering that is generally laid over them are assumed to be smaller than 2" in height and will not cause issues with the current design.

Vibration Testing

SolidWorks vibrations simulations determined that the current design has resonant frequencies at 7.8, 14.2, 16.8, 20.2 and 48.1 Hz along the transverse axis (parallel to the drive axis of the cart). The analysis was done at much higher forces than will be applied to the cart in operation, in order to increase the result resolution. For forces of 1 kN at the above frequencies, deflections on the order of 20 cm occurred. The maximum displacement was found at the top of the shelf side of the cart. These frequencies do not correspond to probable operating conditions; there will no direct sources of vibrations at or above 7.8 Hz, other than robot malfunction. Should the WAM arm oscillate along the transverse axis, vibrations may cause deflections on the order of 2 cm from the norm.

Possible indirect sources of vibrations include travel over a rough, surface with a pattern for which the velocity creates a periodic oscillation of the above frequencies. However, even this would not cause excessive vibration, as this motion is not along the primary axis of resonance. Additionally, further implementation of the robot drive-axis should use this data to ensure the drive motor runs at a lower frequency (RPM << 468).

Additional simulations were done to evaluate the effects of adding I-beam supports to the cart base. The results show that the modified design deflects at a maximum on the order of 1.5 cm from the norm. Even significant structure added along the base does not counteract the main resonant vibration along the transverse axis. Should operation show that this is a concern, the cart will need additional cross bracing between the shelf side and the robot-axis side at a higher point.

Parts Accessibility

Having the robot arm mounted on the rail system allows the arm to have horizontal access to the entire cart, regardless of length. The vertical range of the arm is dependent on the dimension of the arm, in this case the WAM robotic arm. The dimensions of the arm Appendix B were used in the original design parameters and the accessibility testing confirmed that the sizing was correct for the given arm.

In the event of power failure or robotic control failure, the cart needs to be accessible by humans. The open design of the frame allows a worker to reach in from behind the shelves or across the rails and into bins from the front. The ease of human access to the bins means that the possibility of human/robot collisions is quite high. The result of this is that there needs to be a safety mechanism in place to prevent the worker from being injured by contact with the robot moving at high speeds. At the time of project completion, no adequate safety mechanism has been devised.

2.5 Alternative Considerations

Throughout the design process there were multiple considerations that were not part of the final design for particular reasons. These considerations include methods for actuating the motion of the robotic arm mount along the rails, strengthening the overall structure, identifying markers on bins and pallets, foam structures for holding parts within bins and on pallets and a turnable front axle.

Cable Driven Linear Actuation

The motion of the robotic arm along the length of the rail system needs to be governed by an accurate consistent method. Several design options were researched as a means of actuation and each has its benefits and costs. Belt driven actuation would require timing belt precision and belts have the issue of stretching over time which will decrease the accuracy of the timing. Lead screws are strong and should not deform over time; however a lead screw over the entire length of the rail would have flexure due to lack of support and this could lead to seizing in the system. Cables offer the benefits of each system without having the problems of stretching or flexure, provided the cables are of strong enough steel under high enough tension. The main drawback of the cable system is that it requires pulleys on the ends of the cart so that the cables to not rest directly on the cart frame, this adds to the length of the cart but only by the size of the pulleys. The final design does not include the cable system, as it would require much more planning and expertise to produce accurately.

I-Beam Frame Strengthening

As mentioned in section 2.4 Discussion of Results, the amount of angular deflection in the cart is higher than the anticipated maximum. The lack of structural strength across the frame is the main reason that the frame is able to bend so much under loading. To reduce the effect of the loading on the frame, it is necessary to increase the strength of the crossbeams on the base of the frame. Placing I-beams across the base of the frame will increase the rigidity of the structure and reduce the amount of angular deflection present in the system. Another possible way to shore up the strength of the base is to add a ¼” aluminum base plate. The combination of both base plate and beams is the optimum solution. The beams and base plate were not added to the cart due to cost and timeline.

Bin Identification System

Identifying which bin contains the needed parts is something that the robotic arm should be able to do while in operation. Pre-programmed coordinates for the location of the desired bin are not ideal because of the possibility that the arm may lose alignment while active. Radio frequency identifier (RFID) chips offer a simple method of determining which bin is near the arm but signal overlap could cause some difficulty in accurately finding the correct bin. Barcode or quick response (QR) code along with a reflectivity detector system would reduce the number of signals down to one; however to properly read the code, the arm must first locate the identifier.

Position locating is also necessary for ensuring that the arm is passing between the sides of the bin or legs of the pallet and not moving into the space between bins or pallets. By placing calibration markers, similar to those used on crash test dummies as position markers, the arm can center itself on the correct bin and read the identifier tag before reaching in the bin to collect the part. Dealing with the robotic arm control is beyond the scope of this project but it is good to note that these identification systems have been considered in the design and selection of bins and pallets.

Foam Parts Packaging

Parts contained on the cart may come in many sizes and shapes and holding them in a way that allows them to be easily accessible to human and robot requires that the parts are clearly divided and ordered. Some parts are flexible or unbalanced and will move around the bin or pallet as the cart moves around the factory floor. If the robotic arm is required to search for each part and distinguish the parts contained in a single bin, the amount of time to gather the part for the worker will be increased. Placing the parts inside pre-cut foam structures will prevent movement and simplify handling of the parts. Polyethylene foam can be cut into the desired shape and will resist impacts as well as organizing the parts (Thermal Foams Inc., 2012).

Unfixed Front Axle

The current cart has casters fixed at six points on the frame, two in front, two halfway down the length and two at the back. The front casters are swivel casters, the middle pair is fixed casters and the rear pair is swivel casters with brakes. Having the two fixed casters in the middle reduces the amount of excess 'slip' in turning and increases the amount of control in maneuvering the cart. Attached to the front of the cart is a T-bar handle that is meant to give control for pulling the cart around the assembly line but this would ideally be replaced by a better handle system. The current steering system does not lend itself to quick maneuverability but it does work as anticipated in most situations. As a means of increasing control and decreasing turning radius, the front of the cart could be modified to include an axle that is connected to the frame via a joint that allows for rotating the axle under the cart. The axle would also be connected to the handle by another joint so that the handle could adjust to being pulled at a higher or lower angle.

Similar to the control system of a wagon, this axle-handle configuration makes turning corners easier and it even makes it possible for the cart to maneuver is regions where the space between obstacles is on the same scale as the cart length. The added complexity of designing the axle and its connection to the frame make this option not suitable to the current state of the project. The current swivel-fixed caster configuration is sufficient for a proof-of-concept model but in later versions it may be worth considering the unfixed axle option again.

Sloped Bearing Rail Pallet System

An alternative design to the pallet system is to introduce a sloped tray for the pallet to slide down. Instead of the method of pegs, the pallet would slowly slide down a bearing track until it reaches the back of the cart, and is stopped by a back brace while the pallet's horizontal motion is restricted by a wall or pipe on either side. The front would be raised according to the design specifications set by the size of the robotic arm (ie. its ability to fit the hand underneath the pallet). The benefit of this potential design is that it requires little precision by the robotic arm (or human) in order to handle while offering a simpler overall pallet design.

2.6 Physical Model

Figure 12: Final Frame of Cart

Figure 13: Bins on Shelf with Loading

Figure 14: Mounting Flange on Back of Bins

Figure 15: Bottom of Bin Supported Above Shelf By Flange

Figure 16: PR2 Pushing Cart

3.0 Conclusions

The stability and deflection tests show that the delivered cart is stable enough to support the robotic arm and parts loading in a stationary state and provided the crossbeam structure is added to the frame, it is inferred that the structure will also be able to handle the effects of the moving arm. The bin used in the vertical deflection test was capable of holding 50 lbs of the weight without any ill effects, showing that the Akro storage bin system is sufficient to hold the anticipated loading of parts.

The reconfigurability of the CreForm system allows for redesigning the cart to better fit the needs of the situation. Based on the assumption that the cart will be used as a parts storage system to follow a door around an automotive assembly line, the CreForm system is utilized to build the design that would later be made from permanently welding steel tubing.

The robot accessibility test shows that the robotic arm is capable of reaching, and theoretically lifting, the pallets regardless of whether the pallets employ a conical-peg or sloped-leg system of self-alignment. The simple handling of the pallets will allow the arm to carry and hand-off flexible and irregular parts that would be difficult to manipulate directly.

The cart design is also capable of navigating obstacles that exist in a factory setting by avoiding or going over obstacles. The steering allows the cart to have a small cornering radius while maintaining control when towed by an overhead crane. The casters and the flexibility along the length of the cart allow the cart to climb over obstacles, less than 3” in height, that it would encounter in a factory setting.

4.0 Project Deliverables

4.1 Final Deliverables

1) Cart Frame - The final cart frame delivered is designed as a shelving section connected to a rail support structure. The design, as can be seen in Appendix A is consistent with the proposed design and the only changes in the completed frame are the addition of a central set of fixed casters to give added support to the structure and a handle to facilitate towing the cart.

2) Robotic arm mount - The cart contains a mounting plate to support the robotic arm on the rail system. The mount is designed to hold only the WAM robotic arm model and is capable of being mounted on different bearing systems for a different rail system.

3) Pallets - Pallets designed to carry flexible or oddly shaped parts are included as part of the final design. Two alternate pallet designs have been produced as options for use in the proof of concept. The conical peg pallet is a two-part system that includes a base structure that the pegs rest in. The base is to be secured on the frame of the cart by a secure method so that the pallets will not shift greatly during motion. The sloped leg pallet is designed to rest directly on the shelving unit and does not require additional components.

4) Parts and Supplier List - As a means of delivering the sources of the bins, frame structure and rail system, we have put together a parts and supplier list. This list contains links to the sources for each of these components so that any additional builds can reproduce the same cart. In the case of the bins and rail systems, multiple sources are listed as some offer a better option for different situations. The situations that give rise to the use of a particular supplier are described in the comments section of the list.

5) Alteration Directions - Accompanying the final cart design is directions on how to alter the current cart so that it can be changed from a two-meter version down to a one-meter build. These instructions give step-by-step directions such that the cart will not require a large amount of disassembly prior to alterations and will become modular so that reassembly into the two-meter version can be done quickly and effectively.

4.2 Financial Summary

All pricing is in USD, $250 was paid by the stipend from the project lab and the CARIS Lab as a part of their research grant covered the remainder.

Table 1: Pricing of CreForm Materials

Part ID	Description	Qty	Unit Cost	Extended
H-4000GRY	PLASTIC COVERED STEEL PIPE, 4M	13	$11.40	$148.20
HF-4000GRY	FLAT PIPE, PLASTIC COATED STEEL 4M	2	$22.81	$45.62
HJ-1	METAL JOINT SET FOR 28 MM PIPE	30	$2.38	$71.40
HJ-2	METAL JOINT SET FOR 28 MM PIPE	30	$4.53	$135.90
HJ-3	METAL JOINT SET FOR 28 MM PIPE	8	$6.40	$51.20
HJ-4	METAL JOINT SET FOR 28 MM PIPE	4	$3.70	$14.80
MF1-1	METAL JOINT SET FOR FLAT PIPE	4	$2.90	$11.60
MF1-2	METAL JOINT SET FOR FLAT PIPE	2	$4.33	$8.66
J-110	PLASTIC END CAP FOR 28 MM BLACK	20	$0.11	$2.20
ESC-100U-28	CASTER, 28 INSERT, URETHANE, SWVL	2	$17.22	$34.44
ESC-100SU-28	CASTER, 28 INSERT, URETH, SWV, BRK	2	$19.97	$39.94
ESC-100FU-28	CASTER, 28 INSERT, URETH, FIXED	2	$16.99	$33.98
Total Weight:	120.56 LBS		**Total:**	$597.97

4.3 Ongoing Commitment

Following the submission of this report, the commitment to produce the alteration directions will still remain to be dealt with. These instructions will be submitted within one week of the report submission date, April 2nd.

5.0 Recommendations

1) The results of the loading tests demonstrate that the delivered cart acceptably supports the desired loads in a static fashion. The vertical strength of the cart is more than sufficient for the requirements. However, transverse reinforcement is required to reduce the impact of periodic forcing at the resonant frequencies. Extra support along the base of the cart is not sufficient to significantly reduce the displacements from resonance; transverse cross bracing between the shelves and robot-axis is a potential solution.

2) It is determined, in conclusion, that the parts-cart is fully capable of having reconfigurable options in regards to overall dimensions, as well as bin, pallet, and robotic arm sizes. After testing the built parts-cart, a few recommendations must be made. Firstly, it is recommended that the length of the parts-cart be reduced for its purposes as a test-bed in the CARIS Lab. By cutting down the pipe lengths the overall build phase becomes easier and overall cost is reduced; cart sections can be made to link together with appropriate joints if longer carts are necessary.

3) As results show, the robotic arm of the parts-cart is capable of handling either parts in bins or pallets. It is recommended for testing purposes that a sloped self-aligning track system be built to determine the level of simplicity relative to using the conical-peg system. At the time of this report, it is unclear whether a sloped track pallet would be easier to maneuver for a robotic arm than the conical-peg system.

4) The conclusions show that the current caster size used allows the cart to roll over obstacles of up to 3”. As such, it is recommended that, if the parts-cart is required to maneuver over obstacles taller than 3”, larger casters be used. Caster size will depend specifically on the size of the obstacles it must encounter in a factory setting.

6.0 Appendix A – Drawing and Models

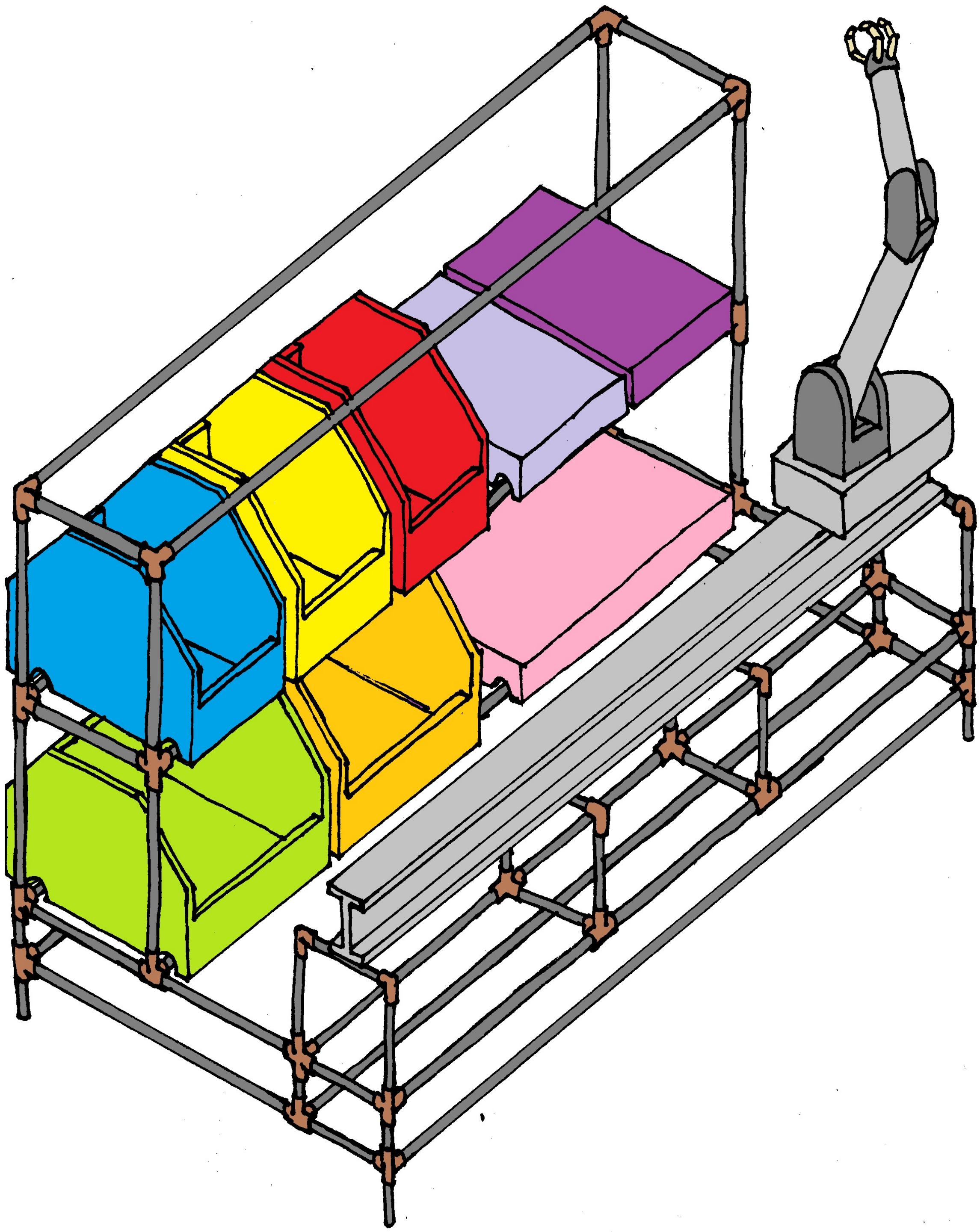


Figure 17: Original Cart Design Sketch

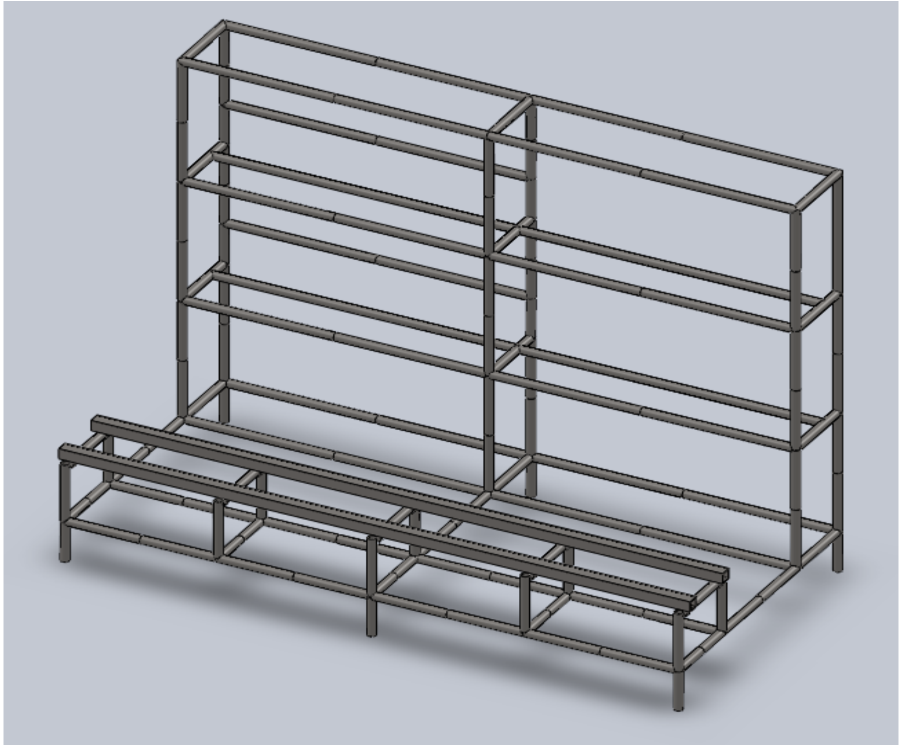


Figure 18: SolidWorks Cart Model

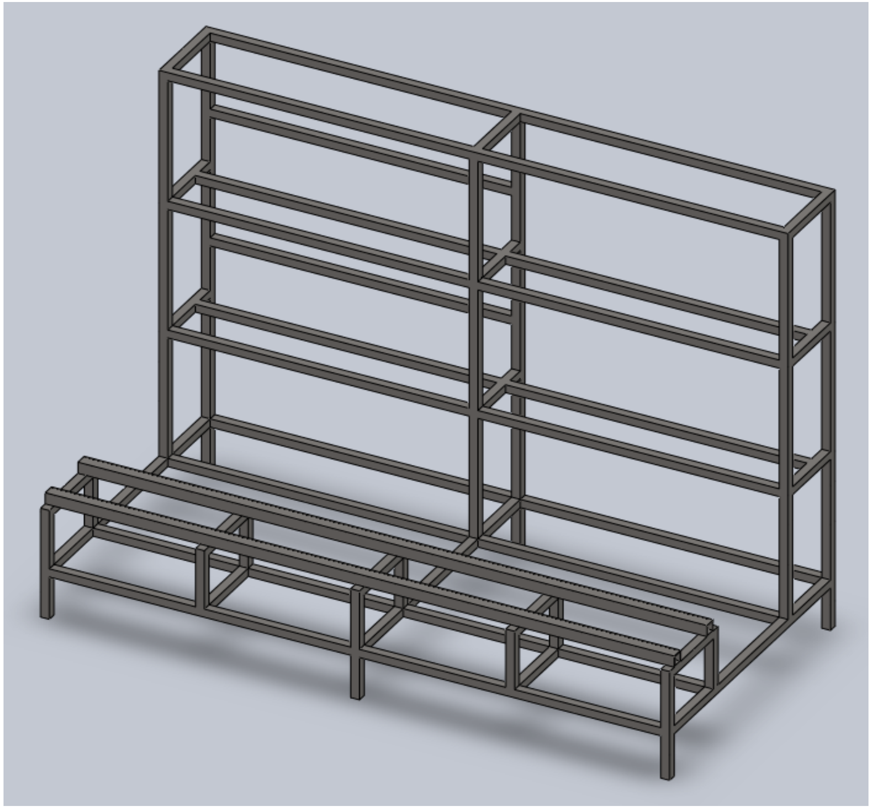


Figure 19: SolidWorks Cart Model - Simplified Simulation

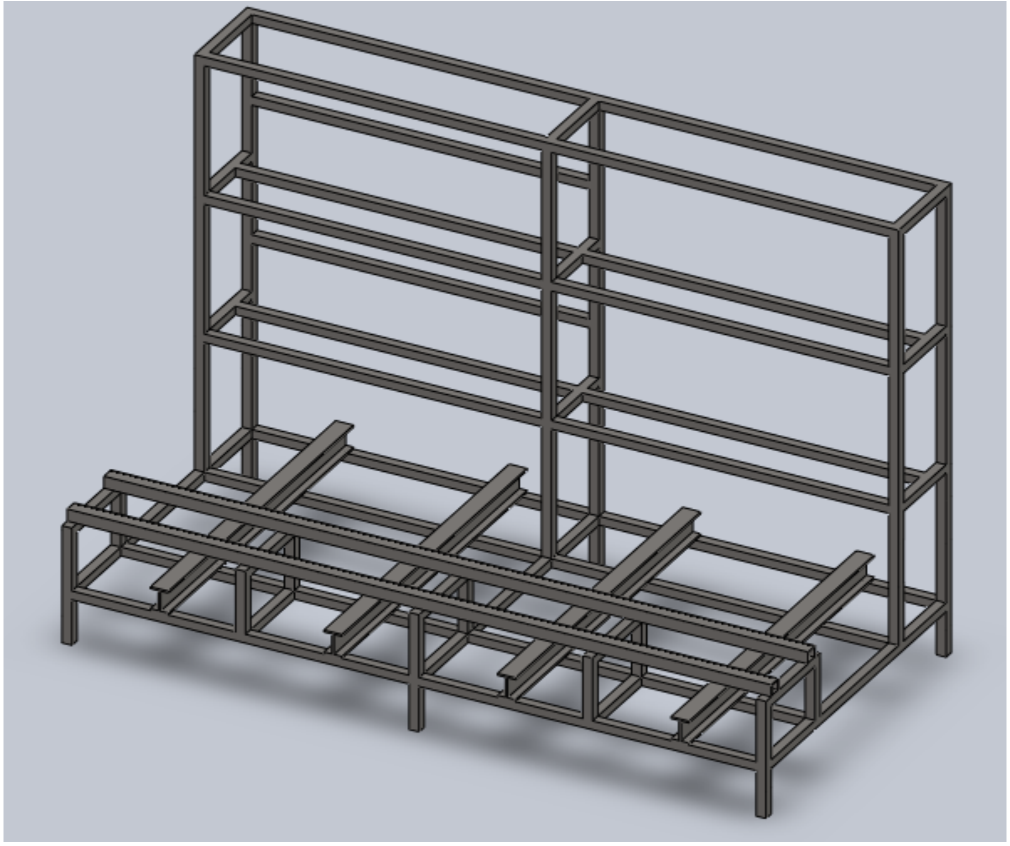


Figure 20: SolidWorks Cart Model - Simplified Simulation with I-beams

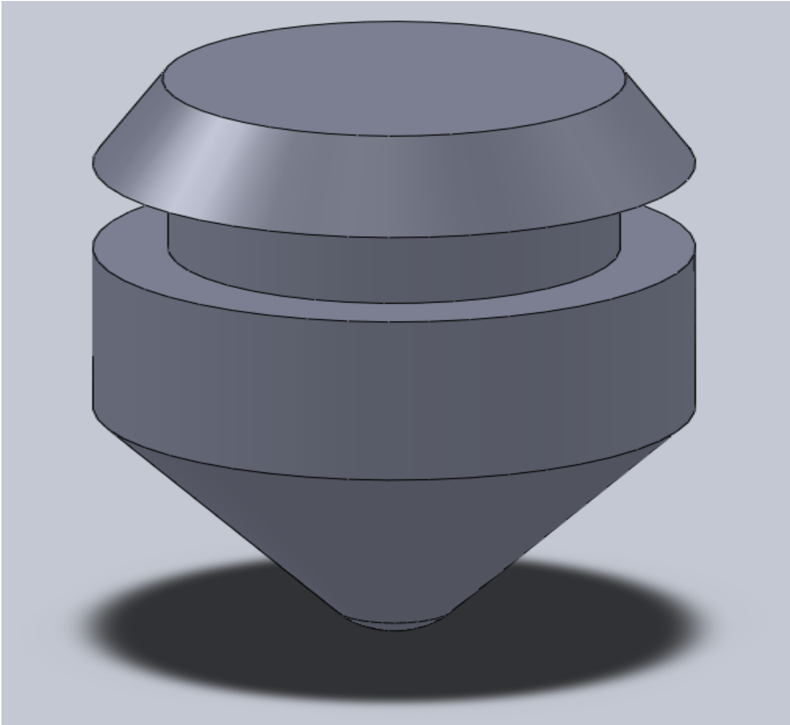


Figure 21: SolidWorks Model of Conical Peg

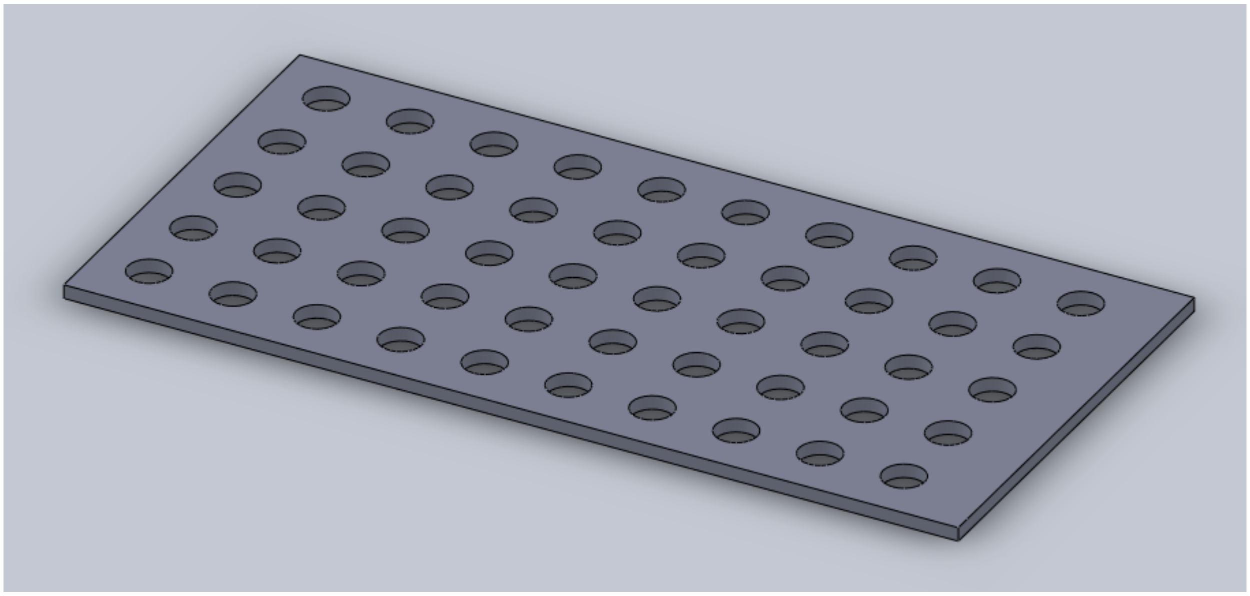


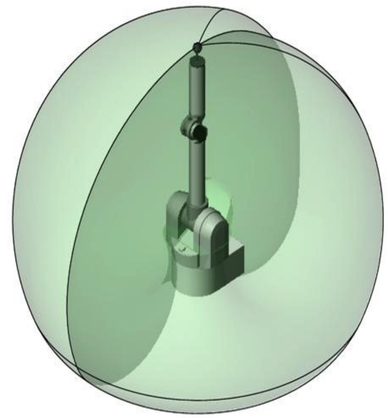
Figure 22: Conical Peg Pallet Mounting Plate

7.0 Appendix B – Spec sheets

WAM SPECIFICATIONS – part #B2529		
Power Requirement (AC Operation)	100-240 vac 1ϕ 50-60 Hz @ 60 watts minimum	
Mobile (DCN) Operation	24-80 vdc @ 50 watts minimum	
Reach	4-DOF 7-DOF	1000 mm 1000 mm
Payload	4-DOF 7-DOF	4 kg 3 kg
Endtip velocity	Max	3 m/s
Mass of robot	4-DOF 7-DOF	25 kg 27 kg
Work volume		3.5 m^3
Repeatability	4-DOF 7-DOF	1000 μm 2000 μm
...with joint encoder option	4-DOF 7-DOF	100 μm 200 μm
Mechanical Stiffness		1.5E6 N/m
Control stiffness		5000 N/m

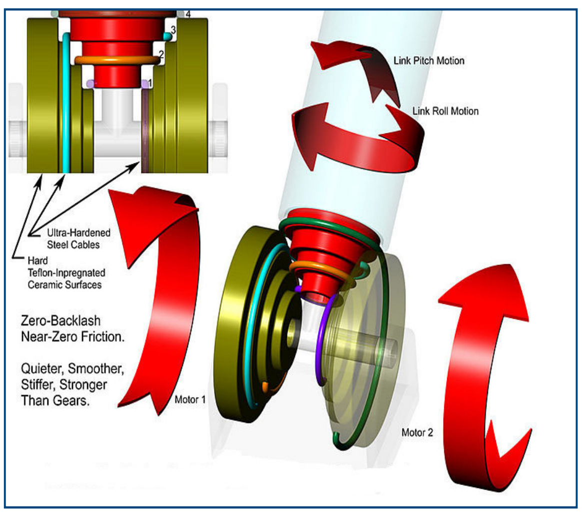
Go to www.barrett.com for complete specifications

TECHNICAL SPECIFICATIONS SUBJECT TO CHANGE WITHOUT NOTICE

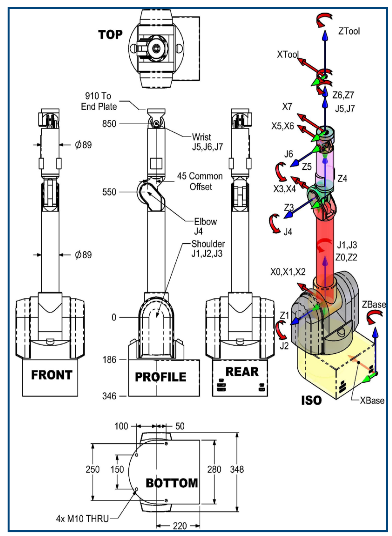


Workspace, Isometric View

The Barrett WAM™ has a generally spherical workspace approximately 2 meters in diameter.



Barrett's Gearless Transmissions



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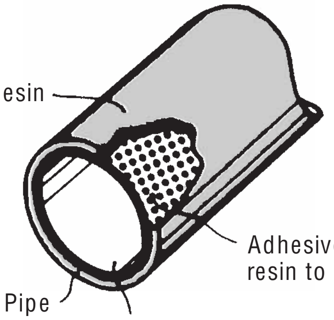
WAM-02.2011

CREFORM TECHNICAL SPECIFICATIONS

Creform Standard Pipe

Creform Pipe is steel pipe with a plastic resin coated outer surface. An adhesive bonds the resin to the pipe preventing separation. The inner surface is treated with a non-corrosive coating.

Creform Pipe Specifications	
Material	Steel pipe [Cold-rolled steel, SPCC-1 approx. 0.7mm (0.03") thick, 28mm; 0.9mm (0.04") thick, 32mm] plastic resin coating
Outside Diameter	28mm (1.10"), nominal 32mm (1.26"), nominal
Weight	28mm, approx, 520g/m (5.5ozs./ft.); 32mm approx. 740g/m (7.8ozs./ft.)
Length	2.5m (8'2"), 3.0m (10') 4.0m (13'1")
Gage	28mm No. 23 32mm No. 21



Note: *28mm is the recommended pipe diameter for general applications because it is supported by most Creform components. 32mm is generally reserved for special purpose applications.*

PreCutting: We offer precut pipe and conveyor as a customer service. Cut to length with a +/-1mm tolerance and each end deburred. A great time saver when assembling.

Bent Pipe: We bend Creform 28mm round pipe as a customer service. Generally, we bend the pipe using a 150, 200, or 250 radius. Larger variable radii also available.

Temperature: Creform is designed for use within the temperature range of 15° to 120°F (-10°C to 50°C).

Chemical Resistance: Please inquire with your specific requirement.

Typical Applications

Slide Pipe

- Steel pipe with low friction plastic coating
- Low cost conveyance option
- For secondary presentation angle
- Use as a shelf surface
- Use as a side guide with skatewheel conveyor
- Strength comparable to regular 28mm pipe

L Channel Slide Pipe

- Steel pipe with low friction plastic coating
- Low cost conveyance option
- For secondary presentation angle
- Use as a shelf surface
- Use as a side guide with skatewheel conveyor
- Vertical lip for side guidance

Flat Pipe

- Holds clip-on plastic hanging bins
- Use as a shelf surface
- Provides a flat surface for labeling
- Provides a flat surface to mount drawer slides
- Strength comparable to regular 28mm pipe

Ribbed Pipe

- HPA and HPB interlock and glue together to create a double pipe beam
- Used to build reinforced cart base
- See Technical Section H for strength information
- Available pre-glued, please inquire

H

CREFORM
TECHNICAL SPECIFICATIONS

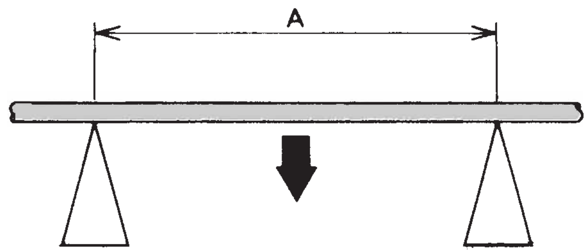
Creform Standard 28mm Pipe Strength

Experimental Conditions

- The pipe rests freely at room temperature on two supports
- A force is applied at 1/2 A at a speed of 50mm/min

A Dimension	Proportional Limit
450mm (1'5")	140kg (308 lbs.)
900mm (2'11")	70kg (154 lbs.)
1,000mm (3'3")	58kg (128 lbs.)
1,100mm (3'7")	52kg (115 lbs.)
1,300mm (4'3")	46kg (101 lbs.)
1,500mm (4'11")	38kg (84 lbs.)
1,800mm (5'10")	32kg (70 lbs.)

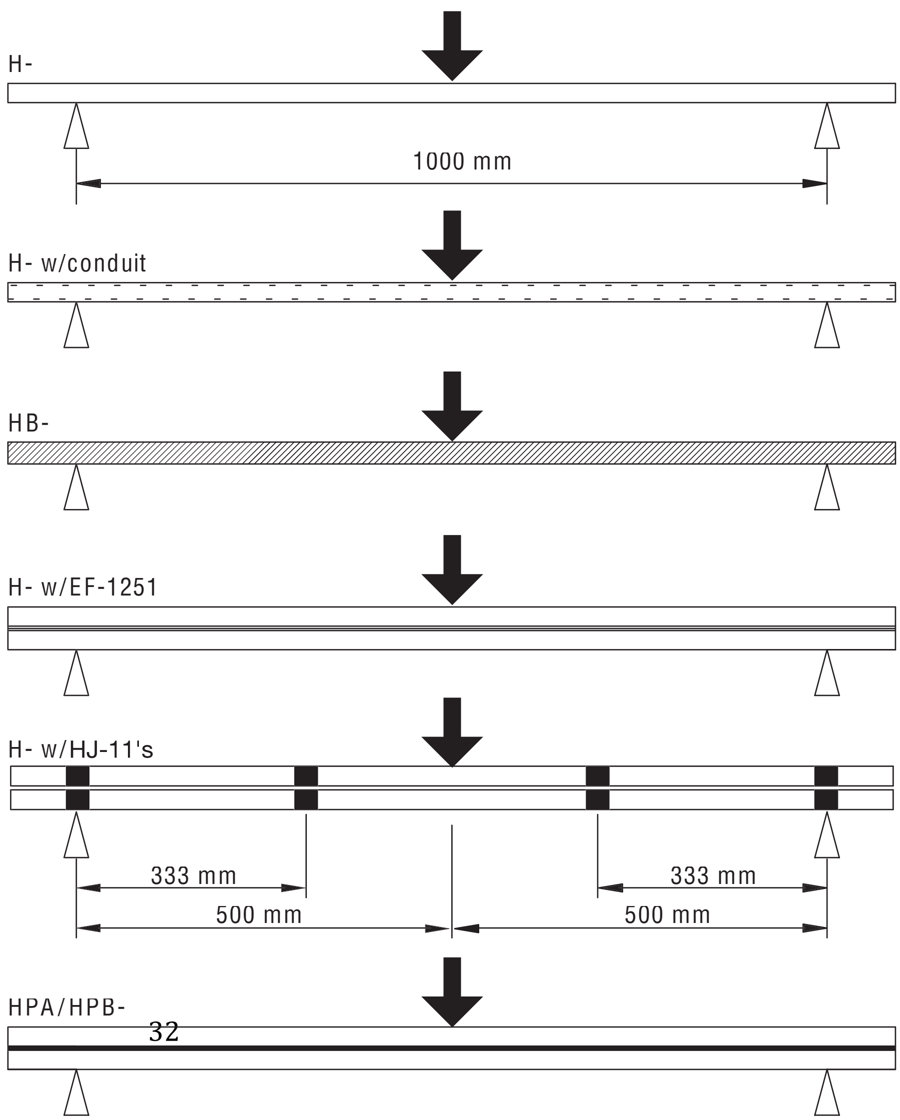
** Proportional Limit refers to the point where any further force would permanently deform the pipe.*



Deflection

Assume a simply supported H- pipe (ø = 28mm) centrally loaded with a 30kg (66 lbs.) load. This deflection will be considered 100%. The deflection of other style pipes and combinations of pipes and joints under the same loading conditions as the H- pipe are shown below.

Pipes	Strength	Deflection
H- pipe (28mm)	100%	100%
H- pipe (28mm) w/ 3/4" conduit inside	180%	78%
HB- pipe (32mm)	194%	60%
H- pipes (28mm) w/ EF-1251	193%	76%
H- pipes (28mm) w/ HJ-11	168%	67%
HPA/HPB- pipe	392%	13%



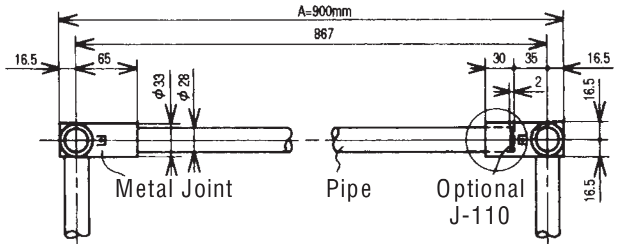
SECTION

Determining Standard Pipe Lengths

The following is true for most Creform joints. Please check the catalog for exact dimensions of an individual joint.

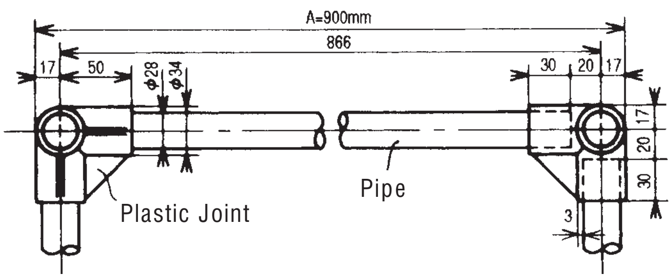
ø28mm

1. Metal Joints



900mm	Outer Measurement A
-33mm	Joint Radius x 2
-70mm	Pipe Length Inside Joint (35mm x 2)
797mm	Pipe Length

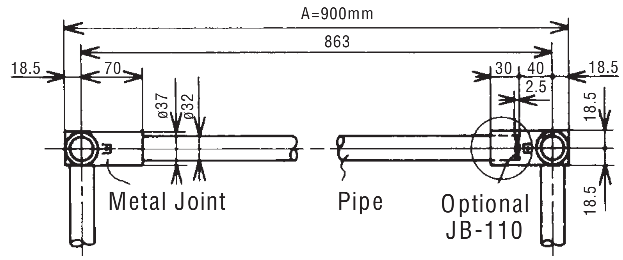
2. Plastic Joints



900mm	Outer Measurement A
-34mm	Joint Radius x 2
-40mm	Pipe Length Inside Joint (20mm x 2)
826mm	Pipe Length

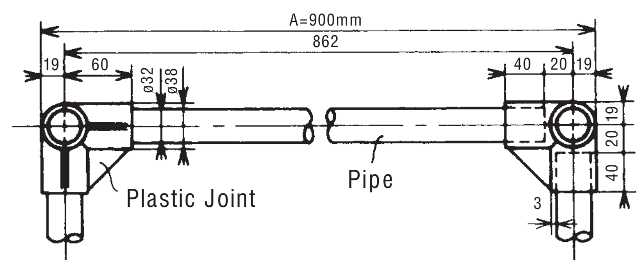
ø32mm

1. Metal Joints



900mm	Outer Measurement A
-37mm	Joint Radius x 2
-80mm	Pipe Length Inside Joint (40mm x 2)
783mm	Pipe Length

2. Plastic Joints



900mm	Outer Measurement A
-38mm	Joint Radius x 2
-40mm	Pipe Length Inside Joint (20mm x 2)
822mm	Pipe Length

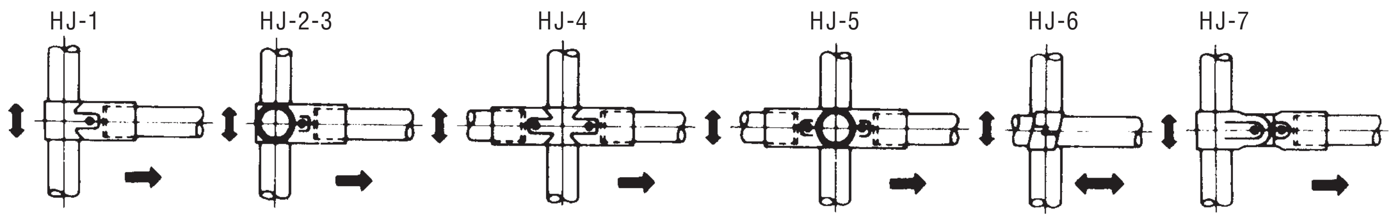
Conversion Chart*

mm	Inches, Dec.	Inches, Frac. Approx.	mm	Inches, Dec.	Inches, Frac. Approx.	mm	Inches, Dec.	Inches, Frac. Approx.	mm	Inches, Dec.	Inches, Frac. Approx.	mm	Inches, Dec.	Inches, Frac. Approx.
4	0.1575	3/16	33	1.2992	1-5/16	37	1.4567	1-7/16	40	1.5748	1-9/16	80	3.1496	3-1/8
5	0.1969	3/16	34	1.3386	1-5/16	38	1.4961	1-1/2	70	2.7559	2-3/4	900	35.4331	35-7/16

** Conversion factor is 25.4mm per inch.*

Metal Joint Strength for Standard 28mm Pipe

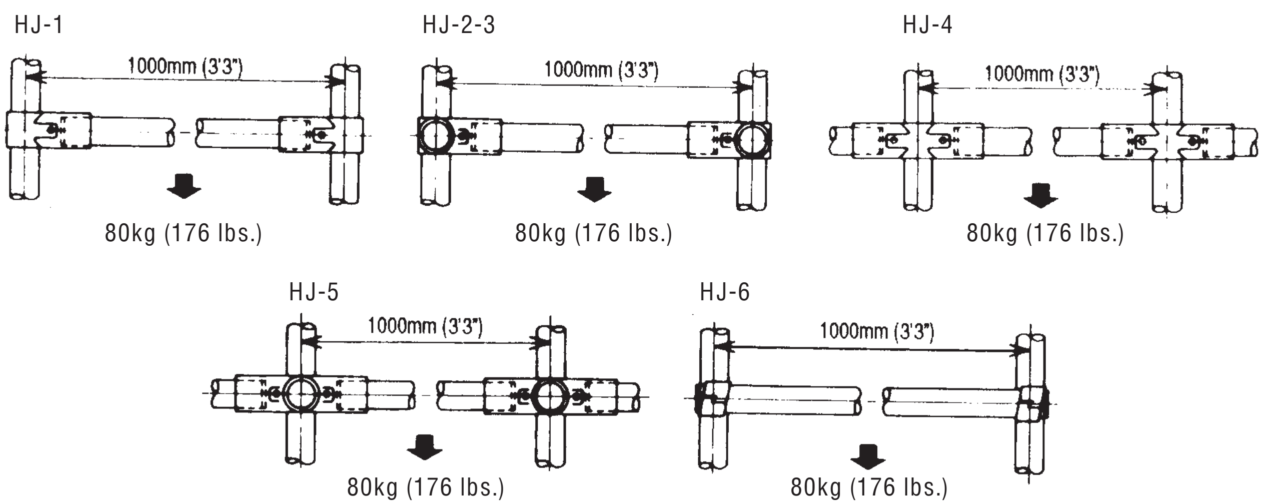
A. The holding strength of metal joints versus a horizontal or vertical pulling force is about 80kg (176 lbs.) These tests were performed at room temperature at a pulling rate of 5mm/min.



B. The amount of force a pipe can withstand before yielding, when attached by various metal joints, can be seen below.

Experimental Conditions

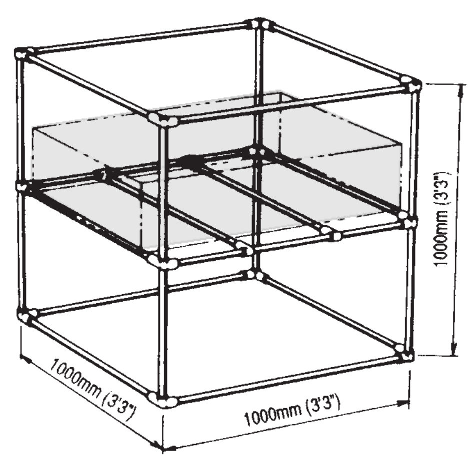
At room temperature, a force was applied in the center of a 1000mm (3'3") length pipe. The force rate was 1kg/min.



C. The maximum force withstood by the shelf in this example was 200kg (440 lbs.) before slipping occurred.

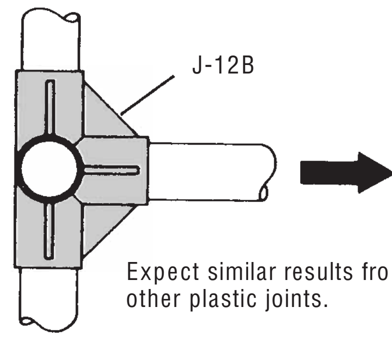
Experimental Conditions

A downward force was applied evenly on a shelf at room temperature and at a rate of 3kg/min.



Note: The above examples refer to metal joints which have been attached at the recommended torque of 9.8Nm (100kg•cm or 7-1/4 ft-lb). These results will not be duplicated with other torque values, or in cases where pipe other than Creform standard pipe is used. Also, they are actual test values without any safety factors added.

Plastic Joints

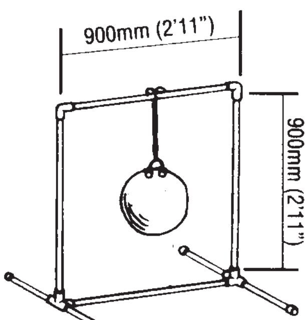


Expect similar results from other plastic joints.

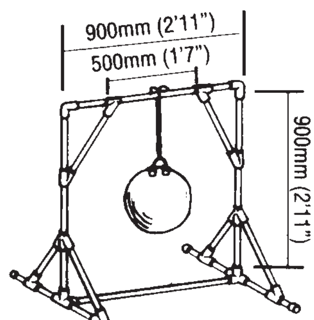
Adhesive Strength for Standard 28mm Pipes & Plastic Joints
Plastic joint J-12B was set aside for one week after bonding with Creform Adhesive. It resisted a maximum pulling force of 800kg (1,762 lbs.)

Experimental Conditions

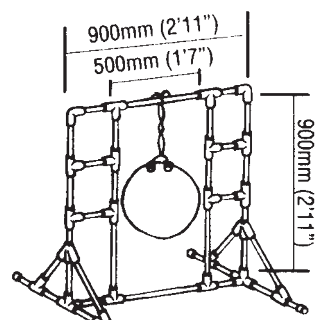
Like other materials such as steel, aluminum and wood, the strength of Creform structures depends on design and assembly techniques. As with all structures, light loads require minimal bracing while heavier loads require reinforced structures. Tests below done at room temperature with a centralized force of 2kg/min.



110kg (242 lbs.)



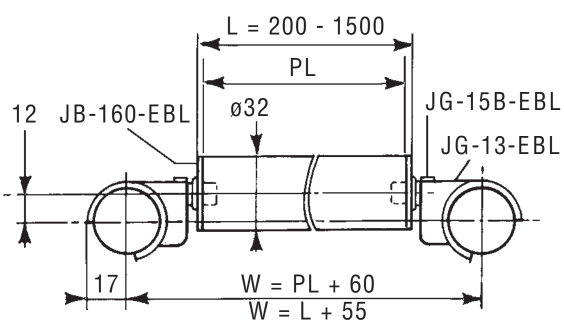
170kg (374 lbs.)



230kg (507 lbs.)

Special plastic joints are used to assemble Creform roller pipes

Roller Conveyors using HBG- or HBGA- 32mm Pipe



Bearing bushings (JB-160-EBL) of roller pipes, bearing pivots (JG-15B-EBL), and holders (JG-13-EBL) are made from specially formulated plastic polymer. This unique combination assures lubrication and maintenance-free conveyance of material under normal conditions as well as in high humidity environments.

This load test was done at 5mm/minute on the roller's center. The maximum loading is given at 1/10 the breaking point for safety purposes.

Roller Length		Max. Loading	
mm	Inch	kg	lbs.
200	8"	20	44
300	1'0"	14	30
400	1'4"	13	28
500	1'8"	11	24
600	2'0"	10.5	23
700	2'4"	10	22
800	2'8"	8.5	18
900	2'11"	7.5	16
1000	3'3"	7	15
1200	3'11"	6	13
1500	4'11"	5.5	12

SECTION

8.0 References

Akro Mils. (2011). *Akro Mils Material Handling.* Retrieved Jan 18, 2012, from Industrial Bins: http://www.akro-mils.com/Products/Industrial/Standard-Storage-Bins/AkroBins.aspx

Barrett Technology Inc. (2012, Jan 1). *WAM Robotic Arm.* Retrieved Jan 14, 2012, from Barret Technologies: http://www.barrett.com/robot/DS_WAM.pdf

CreForm Material Handling System. (2012). *CreForm.* Retrieved Nov 26, 2011, from Material Handling: http://www.creform.com/front_materials.html

Holden Automotive. (2011, Jan 24). *Youtube.com.* Retrieved Dec 12, 2011, from Holden Assembly Line Videos: http://www.youtube.com/watch?feature=endscreen&NR=1&v=pgSabtwLNho

Robson, C. (2012, Apr 1). *Youtube.com*. Retrieved Apr 1, 2012, from Maneuverability Tests: http://www.youtube.com/playlist?list=PL62ED5FE949E03337

Thermal Foams Inc. (2012). *Thermal Foam Packaging Products.* Retrieved Feb 23, 2012, from http://www.thermalfoams.com/packaging/default.asp

Volkswagen Car Company. (2012). *Transparent Factory.* Retrieved March 11, 2012, from Glass Manufacturing Plant: http://www.glaesernemanufaktur.de/

Willow Garage . (2012). *Willow Garage PR2 Robot.* Retrieved Nov 17, 2011, from Overview: http://www.willowgarage.com/pages/pr2/overview