Metrics for Mixed Pallet Stacking

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ABSTRACT

Stacking boxes of various sizes and contents on pallets (i.e. making mixed pallets) is a primary method of preparing goods for shipment from a warehouse to a store or other distant site. Many billions of dollars are spent each year in preparing, shipping, and unloading mixed pallets. Designing the load on a pallet well can save money and effort in all three phases. But what is a good design? In this paper we discuss quantitative metrics for mixed pallets. We have built a graphical simulator called PalletViewer, also described here, that displays pallets being built and calculates metrics.

Categories and Subject Descriptors

I.2.1 [**Computing Methodologies**]: Atrificial IntelligenceApplications and Expert Systems; D.2.8 [**Software**]: Software EngineeringMetrics

General Terms

Algorithms, Performance

Keywords

Palletizing, Simulation, Metrics, Mixed, Pallet

1. INTRODUCTION

Stacking objects (boxes or containers) onto pallets is the most widely used method of bulk shipping, accounting for over 60% of the volume of goods shipped worldwide. A significant portion of the pallets are loaded with boxes (or other containers) of different sizes containing different goods. These are called mixed pallets. Shipping mixed pallets is a primary method of preparing goods for shipment from a warehouse to a store or other distant site. Many billions of dollars are spent each year in preparing, shipping, and unloading mixed pallets. For whole sale items it is estimated that more than 50 % of the consumer price is related to post-manufacturing costs such as shipping and handling.

In the literature, the mixed palletizing domain for which we are developing metrics is often called "the distributor's pallet packing problem". It is one of a set of closely-related packing (or unpacking/cutting) problems, all of which are known to be hard to solve as pure geometry problems. A solution is finding an optimally efficient packing. More details are given in Section 2. The most closely related of these is "the manufacturer's pallet packing problem" in which all the boxes are the same size and contain the same items. That is much less difficult (but still very difficult). We are not focusing on that problem or any of the other variants. We are interested in helping with the real-world mixed palletizing problem, which goes far beyond geometry.

Designing the load on a pallet well can save money and effort in all three phases. But what is a good design? In the Manufacturing Engineering Laboratory of the National Institute of Standards and Technology, we are developing a set of quantitative metrics for mixed pallets. We have gone through two rounds of developing metrics. The metrics from the second round are discussed in Section 3.

We are not developing methods for designing stacks of boxes ourselves, and this paper touches on design methods only briefly. We are interested in methods of calculating and presenting metrics. The primary tool we have for that is called palletViewer, which simulates execution of a plan to make a stack of boxes on a pallet in a 3D view and calculates and displays metrics. PalletViewer is discussed in Section 4. The PalletViewer tool was utilized as the primary evaluation tool for the Virtual Manufacturing Automation Competition which is discussed in section 5. Finally, conclusions are provided in section 6.

2. RELATED WORK

A great deal of work has been done on the purely geometric aspect of palletizing: packing a container of fixed size and shape with the largest possible volume of objects. In mathematical literature, there are both 2-D and 3-D versions of the problem, and the nature of objects to be packed varies from version to version. The problem is often cast as a cutting problem rather than a packing problem – for example, how can a set of moldings be best cut from a cylindrical log. It is well-known that all versions of the geometric packing/cutting problem are, in general, hard to solve. The problem is provably a member of a class of problems called NP-hard (non-deterministic polynomial-time hard). The best algorithms for finding optimal solutions to these problems take computer time that increases exponentially with the number of objects to be packed. For a typical palletizing problem with, say, 50 boxes, the estimated time taken on a supercomputer may be expected to be larger than the lifetime of the universe. Currently, few (if any) researchers believe that an algorithm that can produce an optimal solution in a reasonable amount of time will be found

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in the near future.

Adding other requirements as discussed in Section 3 (such as a low center of gravity) adds further complexity to the problem and has not been addressed in mathematical research. There is general agreement that automatic pallet building systems must use heuristic approaches. With heuristic systems, however, there is no guarantee of being anywhere near optimal. One can only hope that the heuristic methods will produce good results for at least the types of problems for which the heuristics were designed.

The United States Air Force, which ships pallets in airplanes, conducted research on pallet planning in the last decade of the twentieth century and the first decade of the twenty-first [2] [3]. The first of those has a good literature review and bibliography. It also contains C language source code for a pallet planner and substantial documentation of the method implemented by the code. Extensive testing on problem sets generated in-house and elsewhere was conducted.

Bischoff and Ratcliff [5] discussed loading multiple mixed pallets and presented an algorithm for planning for multiple pallets. A flowchart of the algorithm was included. The algorithm was tested on 9600 problems.

Bischoff and Ratcliff [4], almost uniquely among journal papers, presented a number of practical, non-geometric requirements for designing mixed pallet stacks. These included, for example, orientation, load bearing, and stability. They presented a stacking algorithm that has both dense packing and stablility as objectives. They also presented an automatic method for generating problem sets that has been used by other researchers.

Bischoff, Janetz, and Ratcliff [6] discussed mixed pallet planning further.

The collections of boxes in the problem sets of [2], [5], and [4] however, tend to lend themselves to dense packing, whereas real-world collections of boxes may not. Problem sets at the other extreme, where the density of the densest possible packing is near zero might also be devised. Consider, for example, packing very thin boxes in a cubical container where the length of the boxes is almost as large as the diagonal of the floor of the container. Such boxes may be put in the container on the diagonal. If we make the length of the box long enough that the edges of the box touch the sides of the container and we make make the width of the box equal to the length of a side of the container, exactly one such box can be loaded. Since the thickness may be made arbitrarily small, the volume of the box may be made arbitrarily small. For this problem set, the densest possible packing is as close to zero as we choose to make it. As a more realistic example, consider packing the same container with cubical boxes whose side length is slightly more than half the side length of the container. Again, exactly one such box may be loaded. In this case the largest possible density is a little over one eighth ($0.5 \times 0.5 \times 0.5$).

A few commercial pallet planning systems are available [1]. Some of these generate multiple solutions and allow the user to pick one.

[1]Certain commercial software tools and hardware are identified in this paper in order to explain our research. Such identification does not imply recommendation or endorsement by the authors, nor does it imply that the software tools and hardware identified are necessarily the best available for the purpose.

Neither the papers on pallet packing mentioned above nor the commercial systems say much about the metrics themselves, other than packing density. Brief mention is made in [2] of intersection, overlap, overhang, and center of gravity (as described in Section 3).

Along with Pushkar Kohle and Henrik Christensen of The Georgia Institute of Technology, we presented a paper [1] describing the metrics used in the previous version of Pallet Viewer and the Pallet Viewer software. We also described the pallet stacking competition held in May 2010 at the Virtual Manufacturing Automation Competition (VMAC) that was part of the IEEE International Conference on Robotics and Automation (ICRA).

3. METRICS

Roughly speaking, a metric for palletizing is a quantitative measure of some aspect of any of the following:

- one box that is part of a stack on a pallet
- the entire collection of boxes in a stack on a pallet
- a set of stacked pallets
- the process of building stack(s) of boxes on pallet(s).

3.1 Input Data

To evaluate metrics, data is needed. Currently, we are using three types of data files as input for calculating metrics. Parsers are available for each type of file.

- Order file
  - describes the pallets available to use.
  - describes types of package and gives the barcodes of the boxes of each type (thereby giving the number of each type).
  - is an XML data file corresponding to an XML schema.
  - is available before planning.
- Packlist file
  - describes the design of the stack and the plan for building it.
  - can represent multiple pallets.
  - is an XML data file corresponding to an XML schema.
  - is available after planning.
- As-built file
  - describes the as-built stack on the pallet.
  - has a home-brewed format (is not an XML file).
  - implicitly references an order file.
  - is available after the simulation has executed the plan.

The order file and packlist file can represent only four orientations for a box (top up with sides parallel to the sides of the pallet). The as-built file can represent a full 6 degrees of freedom. The limitation on orientations simplifies calculating metrics for planned stacks immensely as compared with what would be necessary if more degrees of freedom were allowed. If there were a full 6 degrees of freedom in plans, a solid modeler would be needed to calculate metrics, and the definitions of some metrics would need to be extended.

The XML schemas mentioned above may be downloaded from [10] and are described in the document "Interface Specification for Mixed Palletizing Competition" which was prepared for the VMAC competition and may be downloaded from the same site.

Data for box positions is given in terms of the coordinate system of the pallet. That (right-handed) coordinate system is assumed to have its origin at a corner of the (rectangular) pallet at the top of the pallet. The X axis lies on one edge of the top, and the Y axis lies on another edge so that the top of the pallet is in the first quadrant of the XY plane. The Z axis is the cross product of the X and Y axes. In normal use, the top of the pallet is horizontal so that the Z axis is vertical. Some of the metrics refer to this coordinate system. In pallet data, "length" is assumed to be along the X axis and "width" along the Y axis.

In the packlist file, each box may be identified by the number giving the order in which to box is put on the stack. This number is used with the metrics to make it clear which box is under consideration.

This section discusses details of specific metrics, but before getting specific, more general discussions of weight support and box robustness are given to set the stage.

3.2 Weight Support Mode

There are at least two different common modes for the way in which boxes are supported by other boxes. What constitutes a good stack is very different between the two.

In one mode, which we might call the *cardboard* mode, when anything (such as another box) is put on top of a box, it is the material from which the box is made that bears the weight. The *cardboard* mode occurs with boxes containing breakable items such as glassware and tomatoes. These boxes may be made of more sturdy material such as wood or thick plastic or may have additional internal supports such as columns at the corners.

In the other, *contents* mode, it is the contents of the box that provide most of the support for any weight placed on top of the box. The *contents* mode occurs with boxes containing relatively robust items such as cans of soda or reams of paper. In the *contents* mode, the material from which the box is made may have very little resistance to compression. The contents have it, instead.

The goodness or badness of metrics such as how much boxes overlap varies widely between the two modes. In *cardboard* mode, overlap is usually a bad thing because the edges of the boxes (the load-bearing part) are not lined up vertically. One web site [9] says overlap (also called interlocking) "can destroy up to 50 % of the compression strength". In *contents* mode, overlap is generally good, since it tends to hold the stack together. The edges of the boxes are not load bearing in *contents* mode. All shippers expect pallets to be wrapped with plastic and possibly also with straps or nets. The wrapping and strapping hold the stack together and fasten it to the pallet, so the benefits of overlap are usually not large. If the pallet is moved from a loading area to a wrapping area, however, it is useful to have a cohesive stack.

The work we have done so far has used pallets of boxes of supermarket items. These are mostly *contents* mode boxes, so overlap has been looked upon favorably.

3.3 Box Robustness

Boxes of different items have different maximum loads and maximum pressures. No box on a pallet should have its maximum load or pressure exceeded. The XML schema for boxes we have been using includes an optional Robustness element, which has as sub-elements: MaxPressureOnTop, SourcePalletLayers, and RelativeRobustness. Currently, our metrics use only MaxPressureOnTop (which is the maximum *allowed* pressure on top). We could calculate the maximum load number as the maximum allowed pressure times the area of the top of the box, but that number would probably not be correct. Also with that number, the maximum allowed pressure would always be exceeded if the maximum allowed load were exceeded, so the "maximum pressure exceeded" error would be triggered, making a maximum load error redundant.

SourcePalletLayers, the number of layers on a pallet of identical boxes on which a product is received, is an empirical measure of robustness. If the manufacturer piled boxes N layers deep for shipment, and they arrived intact, it should be "ok" for the builder of a mixed pallet to do likewise.

RelativeRobustness is an enumeration of VeryWeak, Weak, Normal, Strong, and VeryStrong. This is in order of increasing robustness, but no quantitative meaning has been assigned.

3.4 Specific Metrics

3.4.1 Connections Below

Connections below is a measure of package overlap. A larger number indicates more overlap. For a single box **B**, if the box rests on the pallet, connections below is 1. Otherwise, connections below is the number of boxes below **B** whose tops are in contact with the bottom of **B**.

For a stack of boxes on a pallet, the pallet average connections below is the average of the connections below over all the boxes.

The way the computation is being done, the first layer of a stack always has a pallet average connections below value of 1, and the more layers there are, the larger the pallet average connections below tends to get.

An alternate method of calculating the pallet average connections below might be to disregard boxes directly on the pallet. This would eliminate the effect described in the preceding paragraph and might be more useful.

3.4.2 Overlap

Overlap is a measure of the percent of a box that rests on a support surface. The number ranges between 0 and 1 with 1 being the optimal value. For a single box **B**, the overlap fraction is the fraction of the bottom of **B** that is in contact with the top of the pallet or with the top of some box below it. If **B** has a small overlap fraction, **B** is likely either to be intersecting the pallet or a box below **B** (possible in a plan, impossible in a real stack) or to produce an unstable stack. In the intersection condition, the bottom of **B** is inside the pallet or box below, not in contact with the top of the pallet or the top of the box below. We have been treating a low overlap fraction for a single box as a plan error.

For a pallet, the pallet average overlap fraction is the average of the overlap fraction over all the boxes. This could also be computed by dividing (1) the total area of the bottoms of boxes in contact with the tops of other boxes or the top of the pallet by (2) the total area of the bottoms of boxes. That would usually be a slightly different number since each box would, in effect, be weighted by the area of the bottom of the box. If there were two boxes **B1** and **B2**, the bottom of **B1** was a square millimeter, the bottom area of **B2** was a square meter, **B1** had an overlap fraction of 0, and **B2** had an overlap fraction of 1, our calculation would give an average of 0.5 while the alternate calculation would give something over 0.999.

3.4.3 Overhang

Overhang is a measure of a box or the stack extending outside the pallet.

For a single box **B**, the overhang of each side beyond the four sides of the pallet may be calculated. If there is no overhang, the value is given as 0.

For a pallet, the overhang beyond a side of the pallet is the maximum of the overhangs of all the boxes beyond that side.

Many shippers, including the US Postal Service [11] and UPS [12], require that there be no overhang. The Great Little Box web site [9] says overhang is bad: "With as little as 1/2 inch [12.7 mm] hanging-over, as much as 30 % of their strength is lost!". Overhang will also be undesirable if pallets must be loaded with little clearance between them, a common situation for trucks, airplanes, and large shipping containers. In some situations, however, overhang may be acceptable or desirable.

In order to provide space for netting, the U.S. Air Force [2] requires 5 cm (2 in) of clearance between each side of the stack and a vertical plane through the nearest edge of the pallet. This could be calculated as negative overhang, but we are currently not doing that calculation. It would be simple to do it.

3.4.4 Maximum Pressure on Top

The concept of maximum pressure on top applies to a single box. Exceeding the maximum allowed pressure over a small area might result in a hole being punched in the top of the box. Exceeding the maximum allowed pressure over a larger area might result in the box collapsing.

To determine whether the maximum allowed pressure on top of a box **B** is being exceeded, we calculate the pressure on **B** exerted by each box **T** that rests on top of **B**.

To find the pressure exerted by **T**, let F_t be the total downward force exerted by **T** and A_t be the total area of the bottom of **T** in contact with other boxes.

A_t may be found using the data in the order and the plan giving the positions and sizes of the boxes.

F_t is the weight of **T** plus the force exerted on **T** by boxes on top of it. For boxes on the top of the stack, F_t is just the weight of the box. If we assume that the downward force of each box is uniformly distributed over the bottom of the box, the pressure exerted by **T** on **B** is F_t/A_t. We can calculate the force and pressure exerted by each box on the boxes below it by starting at the top and working downwards. The pressure is found as just described, and the downward force is the pressure times the area of contact.

The assumption that F_t is uniformly distributed over the part of the bottom of box **T** that is supported by other boxes is a naive assumption. The actual distribution of force will depend on several factors such as the elasticity and deformability of the boxes and their contents as well as on the way in which they are stacked. Only a finite element analysis requiring detailed data that is not available could hope to provide a good picture of the actual distribution of force.

The metric for a single box is the maximum pressure in kilograms per square meter exerted on the top of **B** by any other box. If the maximum allowed pressure on **B** has been exceeded, that is reported as an error.

The metric for a stack of boxes is the total number of boxes for which the maximum allowed pressure is exceeded.

If all the boxes in a stack have the same maximum allowed pressure on top, the method of calculating maximum pressure we are using will never return a false report that the maximum allowed pressure has been exceeded since the situation can only be worse if force is not distributed uniformly. However, the method may fail to find a situation in which maximum allowed pressure has been exceeded.

It would be a good idea to check the pressure on the bottom of each box, but no figure for maximum allowed pressure on the bottom is available.

3.4.5 Box Intersections

The format for a design for a stack of boxes allows boxes to be placed anywhere, so it is possible to make a design in which boxes intersect. Such a design is impossible to make, of course, so the design is in error. Calculating whether boxes in a design intersect is easy to do with the current limitation on the orientation of boxes.

For a single box **B**, the metric is the number of other boxes that intersect **B**. It is helpful if the id numbers of the other boxes are given.

For a stack, the metric is the total number of intersection errors. The intersection of two boxes is a single error, not one error for each of the two intersecting boxes.

3.4.6 Center of Gravity

The center of gravity (COG) is a useful measure for determining pallet stability. In almost all real situations, a low COG for a stack of boxes is better than a higher one. The lower the COG, the less likely the stack is to fall over if the pallet is tilted. In addition, it may be important that the XY location of the COG be near the XY center of the pallet, so that a fork lift, truck, or airplane carrying the pallet is not unbalanced. The Air Force is reported to prefer that the COG not be more than 10.16 cm (4 in) from the center of the pallet for a pallet 274.32 cm by 223.52 cm (108 in by 88 in) [2].

The COG of a single box is assumed to be at the center of the box (halfway between each of the three pairs of parallel sides). This may or may not be a good assumption. The input data format does not have a place to put the location of the COG of a box.

The XYZ location of the COG is easy to calculate from the input data. The metrics currently used for the COG are its height above the pallet in meters and its relative offsets from the pallet center in the X and Y directions. The relative offset in the X direction is the difference between the X coordinate of the COG and the X coordinate of the pallet center divided by half the length of the pallet. With that definition: if the value is 0, the COG is at the center of the pallet in X; if the value is 1, the COG is at the +X edge of the pallet; and if the value is -1, the COG is at the

-X edge of the pallet. The relative offset in the Y direction is defined similarly but using the width. The relative offsets provide a measure that is intuitive and independent of the size of the pallet. The XY location of the COG may be easily calculated from the relative offsets as long as the length and width of the pallet are known.

3.4.7 Loading Order Errors

Loading order errors provide one measure of the "buildability" of a pallet. As mentioned earlier, the packlist files we are using for input provide both the design for a stack and a plan for building the stack. Among other things, the packlist specifies the order in which boxes are to be added to the stack. It is almost always necessary in the real world to place all the boxes on which a given box **B** rests before putting **B** on the stack. The metric we are using for a single box is the number of boxes below **B** that are not in place when **B** is put on the stack. The metric for a stack is the sum of those numbers over all boxes. It is helpful if the id numbers of the missing boxes are given.

3.4.8 Number of Boxes on Stack

The number of boxes on the stack is useful for keeping track of progress while the stack is being built and, when the stack is completed, for comparison with the number of boxes in the order.

3.4.9 Total Weight

Shipping charges are often based on weight, and many shippers have a maximum allowed weight for a pallet, so this is an essential metric. Also, the total weight is needed to ensure the load capacity of the pallet is not exceeded. The total weight of the stack (excluding the pallet) is calculated as the sum of the weights of the boxes on the stack.

3.4.10 Stack Height

The stack height is the height above the top of the pallet of the highest point on the stack. This is used for finding the pallet storage volume (and hence the volume density).

Almost all shippers have a maximum allowed height that includes the pallet. Another height metric should be added that includes the height of the pallet. The pallet height, however, is not included in the input data we are currently using.

3.4.11 Volume of Boxes

The volume of boxes is the sum of the volumes of the boxes on the stack. Its primary use is in finding the volume density of the stack.

3.4.12 Pallet Storage Volume

This is the maximum volume of boxes a stack with the current stack height could have (in the absence of overhang). This is calculated as the area of the top of the pallet times the height of the stack. Its primary use is also in finding the volume density of the stack.

3.4.13 Volume Density

The volume density of a stack is a significant measure of the quality of a stack. It is computed as the volume of boxes divided by the pallet storage volume. Its value is never greater than 1 (unless there is overhang).

3.4.14 Total Errors

One more metric is provided for the stack. That is the total number of errors. This is the sum of the total overlap errors, the total intersection errors, the total loading order errors, and the total maximum pressure errors.

3.5 Combining Metrics

Depending on the nature of the goods, boxes, shipping methods, warehouse procedures, and unloading procedures, combining the quantitative metrics to produce an overall measure of goodness must be done in different ways with different weights or thresholds applied.

We have not yet found a method of generating a single score for a shipping situation with a specific set of characteristics. Such a method is desirable since it would save a great deal of time on the part of shippers. Commercial palletizing software generates alternatives from which a user must choose according to his or her preferences.

3.6 Additional Metrics

Several additional metrics may be useful, as follows. For several of these, it will be necessary to revise the input file format.

3.6.1 Connections and Overlap on Top

The metrics listed above for connections and overlap are currently calculated only for the bottoms of boxes. It may be useful to calculate them for the tops as well.

3.6.2 Other Measures of Connectedness

The point of finding connections and overlaps is to get a measure of how well the stack holds together. It may be useful to calculate a more direct measure of holding together, such as the number of connected sub-areas on the top side of a layer (fewer being better). Intuitively, a sub-area is formed by a number of boxes in a layer being linked together by boxes in the layer above.

3.6.3 Families of Boxes

To unload a pallet efficiently, it should be possible to unload all boxes that have the same destination at once without having to move boxes that have a different destination. To support this idea, the order schema has a place to put an identifier for the family of a box. A metric could be calculated giving the number of families that can be unloaded from a pallet without moving other boxes.

3.6.4 Error Metrics

It would be useful to have metrics for more kinds of plan and execution errors. These include:

- the number of boxes that should be on the pallet that are not there.
- the number of boxes on the pallet that should not be there.
- the number of non-fatal syntax errors in the packlist file.

3.7 Other Considerations of Metrics

3.7.1 Multiple Pallets

We have not yet tackled metrics for multiple pallets. For example, if more than one pallet is required, is it going to be better to have roughly equal loads on all pallets than to load all but the last pallet full and put the remaining boxes (which may be few in number) on the last pallet?

3.7.2 Box Orientation

The representation of a plan we are currently using allows placing a box in only four orientations – bottom down with sides parallel to the sides of the pallet. It would be practical to allow a wider range of orientations. As long as the sides of the boxes on the stack are parallel to the sides of the pallet, the difficulty of calculating metrics will not change much. Without the parallel sides limitation, calculating metrics would probably require using a solid modeler.

3.7.3 Location Tolerances

It is practical to treat differences of a millimeter or so in height as unimportant in building stacks of boxes of the size typically stacked on pallets. However, it is not clear how to model a stack with non-zero but negligible height differences or how to calculate metrics in this case.

3.7.4 Box Spacing

A metric for spacing between the sides of boxes should be devised. Some automatic planning systems leave spaces between the sides of boxes and have the edges of every layer line up with the edges of the pallet. Other planning systems leave as little space as possible between the sides of boxes. Some boxes may be safely manipulated by suction grippers holding on to the top of the box. For other boxes, side and/or bottom gripping is necessary. In the latter case, it may be necessary to leave spaces between boxes for the gripper.

3.7.5 Design Vs. Plan

Currently, the packlist we are using specifies both the design for the stack and the plan for building the stack. The plan includes waypoints for each box as it is loaded onto the stack. There are many ways in which a given design may be built, and some are more efficient than others. In addition, some designs are easier to build than others. Metrics might be developed both for the buildability of designed stacks and for the efficiency of plans for building a stack with a given design.

For evaluating plans that include specific paths (as they do in the current plan format), one metric might be the number of times boxes being loaded collide with the partially built stack. To calculate that, a solid modeler may be necessary.

4. PALLET VIEWER

4.1 Functionality

Pallet Viewer was originally built at the Georgia Institute of Technology. We have made major revisions twice at NIST. The first NIST revision was described in [1]. The latest NIST revision is described here.

The Pallet Viewer utility displays in a 3D color view a pallet and the as-planned stack of boxes on it. Figure 1 shows a typical Pallet Viewer image. The Pallet Viewer executable is called with at least two arguments: the name of an order file and the name of a plan file. A third, optional, argument may also be given: the name of an as-built file. If the third argument is given, the Pallet Viewer shows the as-built stack in a color wire frame view off to the side of the as-planned stack.

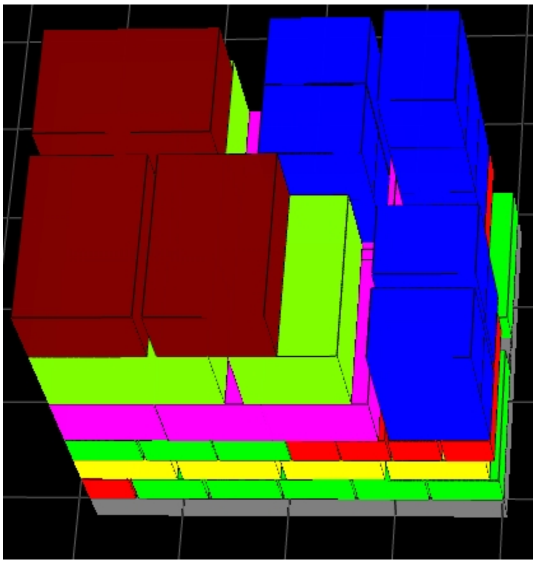

Figure 1: Pallet Viewer Image

Pallet Viewer calculates and displays 23 metrics for the as-planned stack, as shown in Figure 2. These are as described in Section 3. In addition to what is shown in Figure 2, the following additional information will be printed for the current package.

- If the overlap fraction is less than 0.4, "Error!" is printed after the value of the "Overlap fraction".
- If there are intersection errors, the package numbers of the packages that intersect the current package are shown on the "Intersection errors" line immedately after the number of errors. All packages are checked for intersections, not only those shown in the picture.
- If there are loading order errors, the package numbers of the packages that should be under the current package but are not on the stack are shown on the "Loading order errors" line immedately after the number of errors.
- If the maximum allowed pressure on top is exceeded, "Error!" is printed after the value of the "Maximum pressure on top". The value shown for maximum pressure on top is for the complete stack.

The stack of boxes shown in Pallet Viewer may be built or unbuilt by using keyboard keys. The metrics are calculated for all partial stacks when Pallet Viewer starts. Each time a box is added or removed, the metrics for the current package and current partial stack are displayed. The metrics and the stack are shown in different graphics windows. The current view may be saved in a ppm (portable pixmap image) graphics file. The ppm file combines the two windows into a single image.

The Pallet Viewer is a C++ program using OpenGL graphics. Manipulating the view is done entirely with the mouse,

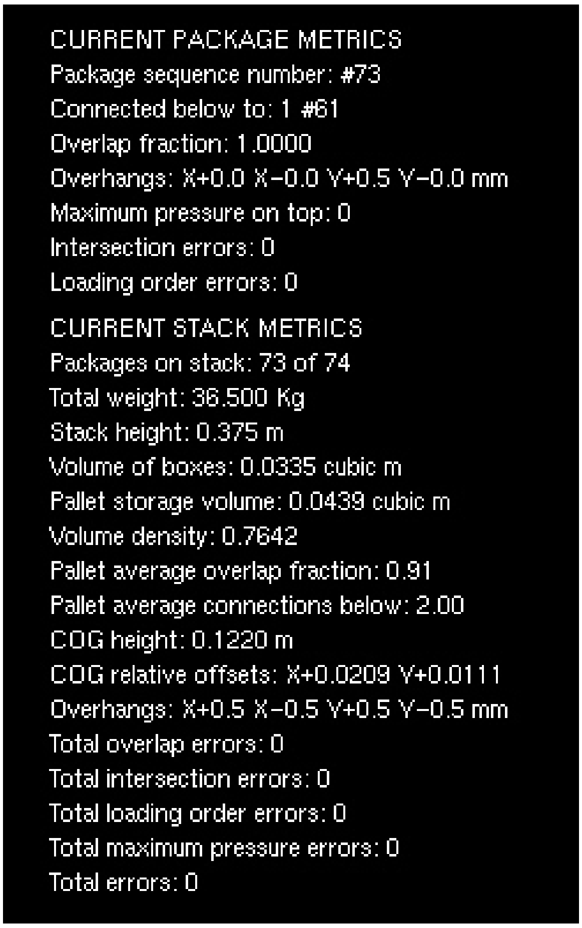

Figure 2: Pallet Viewer Metrics

except that the h key returns the view to its default position. The stack may be rotated and translated. The view may be zoomed in and out.

The Pallet Viewer program is useful for analyzing the process of creating a pallet. Since metrics are calculated for placement of every box on the stack, the software can assess whether the stack will remain stable when it is being constructed. Another important aspect of palletizing is the order in which boxes are put on the stack. By observing the Pallet Viewer display an expert user can to determine if the planner is making motion planning hard or impossible.

4.2 Limitations

The Pallet Viewer application is used to evaluate the quality of a pallet plan based on the geometry of the objects and their placement. Its metrics apply to the geometry and loading forces of a planned pallet and may be used to answer the question, "will this be a good pallet when built?" These metrics don't answer the questions, "how well does this pallet lend itself to being built?" or "when the pallet was actually built, how good was it?" It is a static evaluation that does not evaluate dynamic effects such as objects sliding, tipping or being crushed.

An intermediate step toward dynamic simulation is to use Pallet Viewer to apply static quality metrics after each object has been stacked, so that problems with the intermediate condition of a pallet can be detected. However, since Pallet Viewer does only static analysis, problems such as objects sliding will not be detected.

Dynamic simulation is utilized to supplement Pallet Viewer's static evaluation. There are two aspects of dynamic evaluation: qualitative visualization by an expert, and comparisons of the as-built pallet and the planned pallet to examine object slipping, tipping, crushing or misplacement.

A shortcoming of dynamic evaluation is that the source of problems can't be easily isolated to the pallet building process or the pallet plan itself. For example, if an object slips or tips, it could be due to an improper stacking order as chosen by the robot controller, or it could be due to the plan itself, and no stacking order would fix the problem.

As discussed in Section 2, we use the Unified System for Automation and Robot Simulation (USARSim) [8] to evaluate the pallet build process and resulting built pallet. USARSim runs in real time. As a consequence, the evaluation takes as long as the pallet build process, typically on the order of tens of minutes. This makes it unsuitable as a way to compare many different object stacking plans to quickly select the best plan for execution.

5. COMPETITIONS

The first real trial of the metrics being developed for this effort occurred during the 2010 Virtual Manufacturing Automation Competition (VMAC) [7] that was part of the IEEE International Conference on Robotics and Automation (ICRA) robot challenge. During this event, three different palletizing approaches were evaluated through the use of our metrics. These approaches included a university created neural network learning-based approach, a university created deterministic planning approach, and a commercial product that is commonly used by industry.

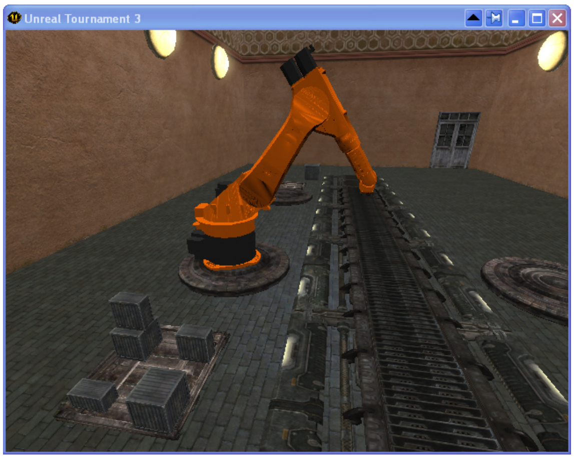

Figure 3: View of the USARSim physics-based simulation of a mixed-pallet under construction.

At the VMAC event, teams were presented with the XML order file and were required to generate a compliant XML packlist file. This file was then passed through the Pallet Viewer software and the values of the metrics were computed. While this provided a measure of the final pallet's quality, it did not evaluate the buildability of the pallet. Therefore, teams were next tasked with running their packlist file on a simulated palletizing cell. This cell was implemented in the Unified System for Automation and Robot Simulation (USARSim) and is shown in Figure 3. USARSim performs a physics simulation that includes friction and gravity, so that problems such as sliding and tipping (which Pallet Viewer will not find) are evident. USARSim runs in real time, however, so it is not able to evaluate plans quickly. USARSim provided an "as-built" file at the end of the pallets construction that could be utilized by the Pallet Viewer software for evaluation of the correctness of the build.

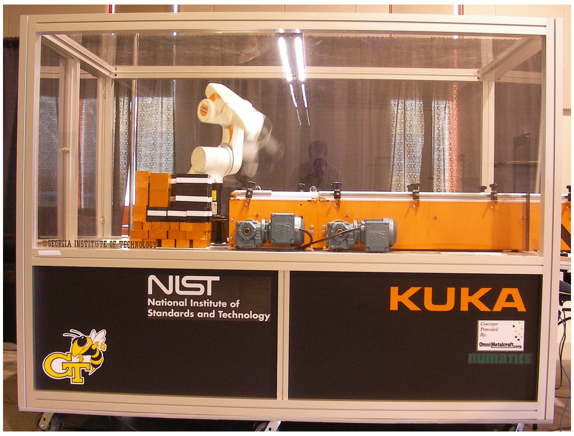

Figure 4: 1/3 scale palletizing cell used during the ICRA Competition

The final step of the competition was to allow successful teams to try and build their pallets on a 1/3 scale palletizing cell shown in Figure 4 This competition is an ongoing event and will be held during the 2011 ICRA conference. Sample palletizing code may be found through the VMAC website and new teams are encouraged to participate.

6. CONCLUSIONS

We have adopted a model of palletizing, used it to define metrics, and held a palletizing competition. A Pallet Viewer utility has been built that calculates the metrics, displays them, and displays a naive simulation of executing a palletizing plan. The USARSim system has been used to simulate execution of a palletizing plan more realistically and produce an as-built description of a stack of boxes on a pallet. We have collaborated with industrial partners to ensure that our work is practical.

The palletizing model we are using is limited in the following ways:

- It supports placing a box in only four orientations.
- It mixes the design of a finished pallet with the plan for producing the design.
- It does not provide for using any buffer space where boxes might be stored temporarily during palletizing.
- No allowance for multiple robots loading a pallet or multiple pallets being loaded.
- No allowance for expressing a constraint on the minimum space between boxes.

We need to improve our palletizing model so that it addresses these limitations. We plan to do that and to continue developing metrics. We are aware of a few additional metrics that might be calculated. We need to consult with more commercial firms to determine what metrics are important in what environments.

We need to develop methods for combining individual metrics in order to produce a single score for the design of a stack on a pallet. Different methods will be needed for different shipping environments.

There is a commercial need for a pallet planner that:

- Uses many of the metrics described in Section 3.
- Includes user preferences for weighting the metrics.
- Includes user preferences while generating designs.
- Can handle multiple pallets.

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