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AN EXTENSION OF DESIGN FOR ASSEMBLY METHODS FOR LARGE AND HEAVY PARTS

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Abstract

Traditional Design for Assembly methods are limited to part sizes between a few mUlimeters to a few tens of centimeters in overall size and to part weights under a few kilograms. Parts in the range of a meter in overall size and weighing a few tens of kilograms are examined in this paper. An experimental plan separates weight mass and inertia and correlates these properties with assembly difficulty and time. When windage, part flexibility and operator fatigue are absent, a set of three parameters serve to model these effects on human assembly performance. Adaptation of this result is made to extend a Design for Assembly methodology.

Word Count: 4448

1. Introduction

1.1 Importance of Design for Assembly

Assembly accounts for the largest single source of direct and indirect costs in most manufactured products today [11. Therefore, attention ought to be paid early in the design cycle to decrease the assembly difficulty for a particular design. The nature of assembly difficulty has been measured and defined by many sources, e.g., [21, [31, [41, [51, [61, [7] and [81. Reductions in assembly difficulty generally decrease assembly time and error rates. As a result productivity improves and the net cost of assembly can be decreased substantially during the manufacturing cycle. The design process must be coupled with the manufacture of the product in order to achieve these improvements. The term Design for Assembly (DFA) encompasses the techniques involved in analyzing and producing a design that is cost effective to assemble. DFA methods generally involve understanding how the geometric features of a part affect its assembly and what properties of an assembly task determine assembly difficulty [9, 10].

From the understanding of a design's influence on its assembly, what is learned can be fed back to the design process to decrease assembly cost a significant part of the overall cost. Since the cost of a change in design increases dramatically as it goes further into the development and production cycles, decisions made early in the design process have significant impact on life cycle cost. Furthermore, the principles drawn from design for assembly methods can be applied to both human and automatic assembly [111 since only the effector and performance characteristics differ in each.

It is useful to measure or quantify assembly difficulty to give a basis for evaluation and comparison of designs and assembly processes before the fact. When the term assembly difficulty is used, it often refers to some metric that has been developed to quantify this concept. One of the most common indicators of assembly difficulty is time in seconds or micro-units [12] (10^{-6} hours). The greater the time it takes to assemble something the more difficult it must be to assemble it. Other measures of assembly difficulty take some form of an index of difficulty that describe assembly difficulty in terms of a self-defined base unit or relative to a base set of part feature values that give the best assembly conditions. A description of several DFA methods will aid in understanding how these metrics are developed and used.

1.2 Design for Assembly Methods

There are several DFA methods in use today. The University of Massachusetts [3] has developed a method based on a large body of empirical data which analyzes the effects of many variables such as parts count, size class, symmetry and shape. The determination of assembly time is based on "quanta" of difficulty along with consideration of the above and other factors.

Xerox Corp. [51 has developed their own method based on empirical data which takes into account direction of assembly, parts count, fixtures, fastening methods, etc., and derives a comparative producibility index (100% is. best) that gives an indication of assembly difficulty relative to a base set of parts and part features. A method based on **a** similar set of task motions producing an open-ended producibility index (zero is best) has been advanced by Hitachi, Ltd., [13]. These two methods infer design recommendations based on reducing those influences which led to poor scores. The user correlates the design features in context with the assembly process and is prompted to improve the design.

A method developed at Westinghouse Electric Corp. [8] also considers the geometric features of a part and the assembly process to determine assembly time. Some of the factors include, symmetry, size, fastening method, insertion direction and handling distance. Like the method of [3], the assembly task is divided into two steps, the acquisition of the part and its actual assembly. The acquisition step concerns the acquisition, handling and orientation of the part or the "gross motion" task. The assembly step is concerned with part mating or the "fine motion" task. This method differs from the previous ones primarily in that the measure of assembly difficulty is measured in information units (bits) [14] and based on the motor capacity of human assemblers. An extension to mechanized assemblers is given in [10].

1.3 A Limitation: Large and Heavy Parts

The methods described above apply well to parts that are relatively small in size and weight. The definition of a small part usually means that a part can be handled on a table by human hands with its size and weight presenting no additional difficulty in assembly. The methods do address the issue of size when the parts are small

enough to affect their handling and assembly. However, the additional difficulty in assembling large parts due to their mass is not adequately treated by any existing method. Methods [3] and [8] distinguish parts which are -heavy or not heavy" by a single threshold value, unrelated to other elements of task difficulty. The influence of large or heavy parts on assembly difficulty is not treated by [5] and [13] at all.

This paper addresses the hypothesis that a large part is more difficult to assemble due to its weight, the inertia from accelerating its mass, the moment of inertia caused by rotating its mass, and the size of the part relative to its assembly clearances. Heavy objects may present an additional level of difficulty for humans and machines and limit their performance when the constant load due to gravity is significant. The mass of an object presents another type of difficulty, inertiaL force, whose effects may or may not be coupled with gravitational force. Likewise, the moment of inertia of an object with respect to some axis of rotation may also add to assembly difficulty. The additional time and effort due factors such as awkward grasps, air resistance (as in large, flat objects), flexibility, etc., are beyond the scope of this paper. The effects of weight, mass, and moment of inertia have been isolated in experiments and correlated to relative part size.

2. Approach

2.1 Metrics

The DFA methodology developed by **[8]** bases its index of difficulty on information theory. This theory defines information as the freedom to choose a set of actions from a particular class of actions [15]. The application of this theory to the human motor system was performed by **[16]** with respect to the amplitude of movement. From experiments, one was able to determine the information capacity of the human motor system, i.e. how much information per unit time a human being can generate. Measuring information capacity involves determining the difficulty for a particular task in which amplitude and resolution is varied. The resulting index of difficulty, Id, in information units, bits is given by:

$$Id = \log2(s/uj), \text{ bits} \qquad (1)$$

The variable, w_9 is the tolerance or resolution required in the task, e.g., the width of the target strips in Figure 1, and s is the amplitude of motion, or distance between the targets. The index of difficulty of a task conveys the information content in performing the task. By measuring the average time, or rate, to perform the experimental task, an index of performance, I_p, can be defined as

$$Ip = l/t * I_d \text{ . bits/sec} \qquad (2)$$

where Id is the index of difficulty and t is the average time per response. The I_p has units of bits/sec and increases when the information rate increases, i.e. performance increases.

Once resulting indices of difficulty and performance are calculated, it is found that the rate at which humans can produce information with their hands and arms, I_p, is independent of the difficulty of the task. Id- The I_p for humans is nearly constant at 100 msec/bit for a wide range of experiments. This figure enables the calculation of approximate assembly time by multiplying the performance index of 100 msec/bit with the index of difficulty of the task which has units of bits.

2.2 Experimental Design

The effects of large parts on assembly difficulty have been conducted through a series of experiments to determine the relationships between a part's weight, mass and moment of inertia to its assembly time. The experiments of [16] served as a basis for the evaluation of the effects of large parts. In the experiments amplitude of motion as well as the tolerance or accuracy of the tasks were varied as parameters to give a range of index difficulties.

Generally, task time can be predicted based on the knowledge of the difficulty of the task and the rate at which the assembler can perform the task. The two metrics introduced above are used to quantify these variables: an index of difficulty, Id (bits), and the index of performance, I_p (bits/msec). Multiplying the Id by $1/I_p$ yields the assembly time. The experiments were designed so that the tasks themselves did not change with increasing weight; thus, the Id remained fixed for a set of tasks. However, increasing weight, mass, and inertia affected the rate in which information could be generated, i.e. the I_p.

Since the existing DFA methodologies do not address large/heavy parts, experiments which determine how these parts change the information capacity of the human motor system were designed to isolate the properties of weight, mass and moment of inertia. These three properties are varied to determine their effects on both the acquisition (gross motion) and the assembly (fine motion) phase. The experiments found trends and relationships between an object's mass, weight and their moments about the arm and the parameters which determine manual assembly such as index of difficulty, time, handling distance, part symmetry, clearance, and assembly direction.

3. Description of Experiments

3.1 Experiment I - Effects of Weight

Part A: Barbell Tapping (Gross Motion Task)

Apparatus & Procedure

For the this experiment, the effects of heavy weight is studied. Figure 1 gives the apparatus for Experiment I a. The subject, S, is instructed to tap the end of a barbell onto one of two target strips alternately while keeping the barbell positioned vertically. The barbell weight can be easily increased or decreased by adding or removing weights. The distance between the two strips is varied among 0.41, 0.81, and 1.42 m (16, 32 and 56 inches) to give different levels of difficulty for the task, and the width of the target strip is kept constant at 51 mm (2 inches). S is given the barbell and asked to make as many taps as possible in 20 sec. A one minute rest period is given in between trials. The experiment is recorded on video tape and timed.

Sequence of Trials

Each S is given 5 different weighted barbells at 0.45 to 12.3 kg (1 to 27 lbs) with amplitudes at 0.41 to 1.42 m (16 to 56 inches).

Part B : Barbell Insertion (Pine Motion Task)

Apparatus & Procedure

The effects of weight on fine motions are isolated in this experiment, and the apparatus is detailed in Figure 2. The subject S, is to repetitively insert one end of a barbell into one of two holes while keeping the barbell positioned vertically. By introducing plates with holes for insertion, a fine motion task is created. The times for the gross motions of moving from one plate to another are subtracted off based on the results of experiment I a.

The barbell weight can be easily increased or decreased by adding or removing weights. The clearance of the hole is varied from 1.6, 0.8 and 0.4 mm (1/16, 1/32 and 1/64 inches) to give different levels of difficulty for the task. S is given the barbell and asked to make as many insertions as possible in 20 sec. A one minute rest period is given in between trials. The experiment is recorded on video tape and timed.

Sequence of Trials

Each S is given 5 different weighted barbells at 0.45 to 12.3 kg (1 to 27 lbs) and hole clearances of 1.6 to 0.4 mm (1/16 to 1/64 inches).

3.2 Experiment n - Effects of Mass

Suspended Barbell Tapping

Apparatus & Procedure

To isolate the effects of mass from the weight requires removing the gravitational force. This experiment is performed by suspending a thin wire from the 7th floor of a building and attaching the barbell at the end, thereby creating a pendulum with a negligible restoring force with respect to inertial forces. The apparatus for this experiment is shown in Figure 3.

The subject, S, is to move a barbell suspended on a long wire in a horizontal direction to tap a sliding sleeve vertically onto one of two holes. Again the barbell mass can be increased or decreased by adding or removing weights. The distance between the two holes is varied from 0.41, to 1.42 m (16 to 56 inches). S is given the barbell and asked to make as many taps in 20 sec. A one minute rest period will be given in between trials. The experiment is recorded on video tape and timed.

Sequence of Trials

Each S is given 4 different weighted barbells at 1.8 to 15.5 kg (4 to 34 lbs) with amplitudes at 0.41 to 1.42 m (16 to 56 inches).

3.3 Experiment in - Moment of Inertia

Rotating Disc

Apparatus & Procedure

For many assembly tasks, moments about the wrists and arms can increase assembly difficulty. This experiment isolates the effects of a large moment of inertia on assembly. The study is performed for one axis about the forearm since this is the axis that most frequently encounters large moments in assembly operations. The apparatus is shown in Figure 4.

The subject, S, is to rotate a disc repetitively through an angle of 90 degrees within some tolerance range. S is to grasp the handle on the disc such that it will longitudinally face S. The moment of inertia about the arm can be changed by adding different sized discs onto the rotating shaft. S will be asked to make as many cycles as possible in 20 sec. The experiment is recorded on video tape and timed.

Sequence of Trials

Each S is given 3 different sized discs, small, medium and large, with their corresponding moments of inertias for a total of 3 runs each.

4. Experimental Results

The Design for Assembly methodology of [8] divides the assembly task into two phases: acquisition and assembly. Results from experiments I a, I b, II and III indicate that the effect of large and heavy parts is most evident in the acquisition phase of assembly. This phase involves acquiring the object from an initial position and moving it to the proximity of the mating part where part mating occurs. This class of actions can be differentiated as the gross motions in an assembly task and thus involves the handling distance acquisition factor. Actual assembly occurs when two parts are actually put together after being oriented and brought within 3 mm of each other. Features which affect this second phase include clearance and direction of insertion. For actual assembly operations, local or fine motion effects are considered in determining assembly time.

From the experiments, a linear relationship between weight and Ip is found for gross motions whereas effects on fine motions such as clearance show no clear trends. The reciprocal of the index of performance, $1/I_p$, is plotted against the weight, mass or moment of inertia for each experiment run in Figures 5 through 8 and show the results for each of the experiments.

Since the slopes of these graphs are linear for Experiment I a throughout the experimental range, increasing the weight is found to affect performance in a proportional way. Finding the slope value by means of a first order curve fit results in a constant that relates weight and the index of performance. Hence this slope can be used to interpolate between weight ranges for new I_p's. Results shown in Figure 5, indicate that weight is related to performance by an average constant slope of 8.78 msec/bit-kg (3.99 ms/bit-lb) after taking values from those curves which start with an offset of 100 msec/bit for 0.45 kg (1 lb).

Experiment H also supports the results of Experiment I a and are consistent with the theory that increasing the weight decreases the performance, i.e. increases 1/Ip. Results graphed in Figure 7 show clearly that there is a linear relationship between mass and the index of performance. In this experiment, gravitational force was eliminated by using a pendulum which isolates the effects of mass alone. The inertia force of a moving mass is found to increase $1/I_p$ linearly as mass is increased linearly. The linear curve fits in Figure 7 show this relationship clearly as the coefficient of determination is almost 1.00. Interestingly, the slope value of mass verses $1/I_p$ is approximately 9.02 ms/bit-kg (4.1 msec/bit-lb) which to first order is equal to the 8.78 msec/bit-kg (3.99 msec/bit-lb) from Experiment I a. This suggests that mass and weight effect $1/I_p$ in a similar way and their influences are not decoupled from each other when handling a part.

In the third set of experiments, effects of rotational inertia or moment about an axis are investigated when rotating parts or when a large bending moment is experienced during assembly. The graphs of Experiment III in Figure 8 show the relationship between the moment of inertia about one axis and $1/I_p$. The regression also indicates a linear relationship in this case. The average slope of moment of inertia verses $1/I_p$ is about 358.6 msec/bit-kg-m^2. The axis of rotation was about the axis of the subject's forearm for this set of experiments. The large slope change suggests that small changes in the moment of inertia of a part may have large effects on assembly time.

For **the** fine motion tasks of the experiments, the graphs of $1/I_P$ verses **weight** in Figure **6** show irregular results as weight is increased. The irregular results and lack of trends indicate that for the fine motion tasks, weight and mass do not influence performance in assembly. Moreover, as clearance is varied no recognizable trends emerge as well. An explanation for this is that the inertial forces are minimal since the accelerations are almost zero once a part has been brought relatively close to its mating surface. Since the insertions were done downwards, weight may be more of an aid to assembly from this direction rather than a liability. It would be interesting to see how weight affects insertions upward or in other directions, and this may be a future direction for this research.

In summary, this set of experiments initially indicates that there is a relationship between a part's weight, mass and moment of inertia and the index of performance, I_p, during the acquisition phase of assembly. Large and heavy parts are shown to affect acquisition time when parts are greater than 4.5 kg (10 lbs), consistent with [3] and [8]. Thus a heavy part's contribution to the assembly difficulty is apparent in the handling distance for a task. However it does not seem that large parts have an affect on performance when dealing with clearance and fine motions. The slope values for computing the $1/I_p$ for a given weight are tabulated in Table 1 and can be used to calculate acquisition time for a given handling distance.

5. Application to DFA Method*

For **the** large/heavy parts identified, a predicted assembly time can be calculated by the DFA method given the Id for a task. The Id can be converted to a time value by multiplying it with an associated index of performance, I_p, based on the weight of the part. It is assumed initially here that the effect of large/heavy parts on performance is isolated from the effects of weight (which include the effects of mass) alone since the slope values from Experiments I & II are almost identical based on weight. Since the performance rate of humans are considered to be constant for negligible weight, the resulting I_p is calculated with a base offset of 100 msec/bit in the formula

$$1/Ip = 100 + m^*weight \text{ (msec/bit)} \qquad (3)$$

where m is the slope value taken as 8.8 msec/bit-kg (4.0 ms/bit-lb) from the experimental data. This I_p is used to compute the acquisition time only, because large weights did not seem to effect assembly time.

The effects of inertia can be included only with knowledge of the moment of inertia of the part as it is grasped. Its effects are present only if there is a moment about the forearm or a rotational motion associated with the task. This situation occurs during the acquisition phase when parts must be aligned through large angles. Difficulty based on part shape with negligible inertia is linear with respect to an Id based on orientation angle and yields a constant performance rate of about 100 msec/bit for human assemblers. For non-negligible inertia, the resulting I_p is then calculated with a base offset of 100 msec/bit in the formula

$$1/Ip = 100 + n*inertia \text{ (msec/bit)} \qquad (4)$$

where n is the slope value taken as 358 msec/bit-kg-m2 from the experimental data. This I_p is used to compute the acquisition time only, because inertias are not included in assembly time predictions. In practice there may be difficulty in determining the moment of inertia of a part which depends on grasp. Choosing the largest inertia for the part along a principle axis would yield conservative estimates.

6. Verification with a Product Design

The DFA extension to large and heavy parts was verified on a product design and compared with assembly time experience. A device for transport of mail in a post office (The Carrier Mail Transporter (CMT) [17] designed by the Carnegie Mellon Research Institute) included a representative number of large parts that exhibit the weight, mass and moment of inertia characteristics that increase assembly difficulty. A drawing of the CMT system is shown in Figure 9 and the large parts selected for evaluation is given in Table 2.

For each part, a DFA acquisition analysis was performed to give the predicted assembly time taking the weight of the parts into account, see Table 3. The predicted time values were validated by comparing them to actual assembly times for the large/heavy CMT parts. Experimental/actual times are listed with the predicted times using the method of calculation prescribed in the previous section. Parts are considered heavy when they are over 4.5 kg (10 lbs), and the effects of weight and mass were applied to these.

Simple pick and place experiments were designed for the CMT parts to find the acquisition times. Assembly of the actual parts during testing generally required the subject to move some of the large parts up to 1 m (40 inches) to their final assembly locations. Extra time was taken into account for the additional motions encountered when handling large and heavy parts. Body motions such as turning and walking are quite common, and the times have been well tabulated in [12]. These times for turns and walking are included in the calculation of the predicted times.

The results of these assembly experiments are given in Figure 10. They show that the predicted times correspond well with the actual times for six of the eight the parts listed. The experimentally derived slope values give a reasonable estimation of the $1/I_P$ value and the resulting time for assembly of large and heavy parts.

Two parts yielded inconclusive results, the bumpers and gussets. These parts are light weight, but long. We observe that the assembler spent additional, unpredicted, time in handling the parts prior to mating. Part mating required alignment to existing holes and the addition of nuts and bolts. Other large parts in this product not evaluated, viz, those which required handling by two assemblers. It is not known how the interaction of two assemblers affect assembly time, and whether the I_p, Id or both are affected. At present DFA .methodologies do not support multiple assemblers.

7. Conclusions

The effects on assembly difficulty presented by large and heavy parts have been investigated by designing and performing experiments that isolate the influence of three main properties of large and heavy parts, i. weight, ii. mass and ill. moment of inertia. An understanding of their effects on assembly time and human performance has been gained. Weight, mass and moment of inertia appear to have a linear relationship with the index of performance. The weight effects are indistinguishable from mass effects since the change in I_p is the same for test parts. Moment of inertia appears also to follow a linear relationship with assembly time. As each of these parameters increases individually, $1/I_p$ increases linearly.

Slope values relating I_p to weight have been used to model and predict the assembly time of parts from a test product. The comparison between predicted and actual times indicate that the derived slope values are accurate for predictive purposes. The DFA method of [8] has been extended to treat large and heavy parts up to 18 kg (40 lbs) and 0.3 kg-m^2 by applying the formulas given by equations 3 and 4. Finally, it is noted that the conclusions reached can be applied to other effector systems governed by I_p, Id values, such as certain robots and automatic assembly systems.

Future work in extending this research include several effects of large and heavy parts that still need to be investigated. The effects of fatigue or number of repetitions and performance have not been considered here. The limits for weight set by work rules in certain industries may be a useful starting point. For large parts that are not heavy, windage forces may be large compared to the gravitational and inertia! forces. In addition, flexible parts may present additional difficulty in assembly. Finally, there are unanswered questions relating to handling of parts by more than one assembler. These effects are interesting and relevant topics for future work in the extension of the DFA theory and methodology.

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Table 1. Experimental Slope Values for Weight, Mast, and Moment of Inertia

Property	In slope
Weight	3.99 msec/bit-lb
Mass	4.10 msec/bit-lb
Moment of Inertia	358.6 msec/bit-J

Table 2. Heavy CMT Parts Studied

Part Name		
1. L/R Lower Beams		
2. Slides	a) 36 in.	
	b) 48 in.	
3. Side Sheets		
4. Side Beams		
5. Parcel Box		
6. Parcel Box Shelf		
7. Bumper		
8. Gusset		

Table 3. DFA Analysis of Heavy CMT Parts

Acquisition

Part Name	Feature/ Boss or Groove	HandUnf Distance	Size*	Shape	H-JJJ Con	Diffkulty Level Per Piece	Difficulty Level	Weight Z	Predicted Time	Adudl Timg
14. Ltt Lower Beams	1.0/100	•13	-	Pie-Oriented	Easy	1.62	3.24		1.02	1.15
15. Slides						It.74	149.«2			
36 in. (4)	1.0/1.00	1066	-	Pie-Oriented	Heavy	237	io.2«	11	3.61	435
4«in.(2)	1.0/100	1066	-	Pie-Oriented	Heavy	Z57	5.14	15	3.S2	4.66
Belli (24)	2t.CV7.00	500	«0(c)	HexPm	Easy	33	79.2			
Nuts (24)	1.0/100	500	64(0	Hex Nut	Easy	23	55.2			
16. Side Sheets (2)	1.0/1.00	1524	-	Pie-Oriented	Heavy	3.17	4.34	17	5.13	4.70
17. Side Beam (4)	1.0/1.00	1000	-	Pie-Oriented	Easy	1.68	6.72	2	4.04	4.60
If. Parcel Boi										
Parcel Box	1.0/1.00	1000	-	Pie-Oriented	Heavy	1.61	6.72	103	1.19	1.76
Parcel Box Shelf	1.0/1.00	113	-	Pre-Oricmed	Heavy	1.62	6-41	73	1.05	1.07
Front Cover	.7577"	500	-	Atymmeiric	Eaty	4.22	4.22	2		
Rivet Gun	1.0/1.00	500	-	Asymmetric	Heavy	4.2	4.2			
MoveftPot.Gun(23)	l.tvi.o	100	-	Sphere	Easy	I	23			
19. Bumper (2)	1.0/1.00	•13	-	Pie-Oriented	Easy	1.62	3.24	1	3.71	*6.10*
19. Gutatt (2)	1.0/1.00	813	-	Pie-Oriented	Easy	1.62	3.24	1	3.71	*6.10*

Table 4. Predicted and Actual Assembly Times of Large/Heavy CMT Parts

Part [illegible]		Predicted [illegible]	Actual [illegible]
1. L/R Lower Beams		1.02	1.15
2. Slides	a) 36 in.	3.68	4.55
	b) 48 in.	3.82	4.66
3. Side Sheets		5.13	4.70
4. Side Beams		4.04	4.60
5. Parcel Box		1.19	1.76
6. Parcel Box Shelf		1.05	1.07
7. Bumper		3.71	6.10
8. Gusset		3.71	6.10

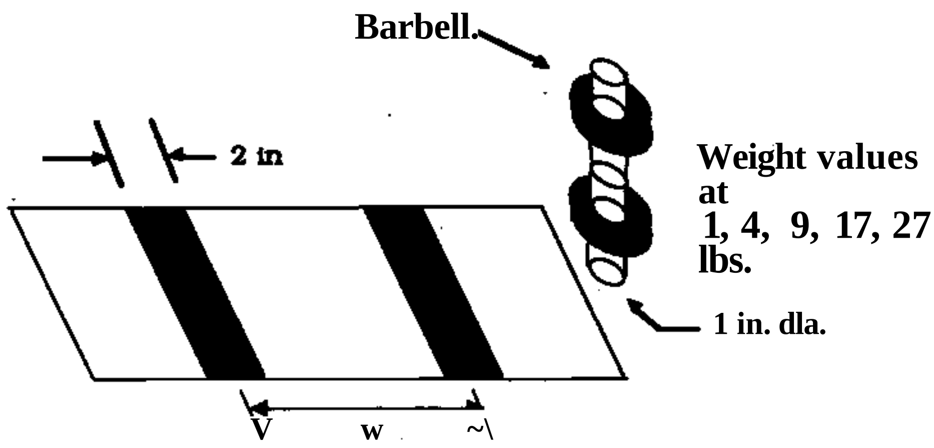

Figure 1. Experiment IA Apparatus

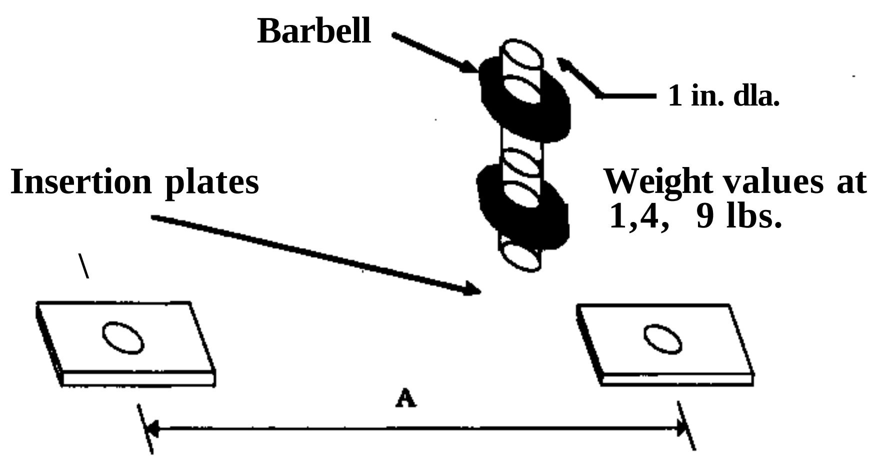

Figure 2. Experiment I b Apparatus

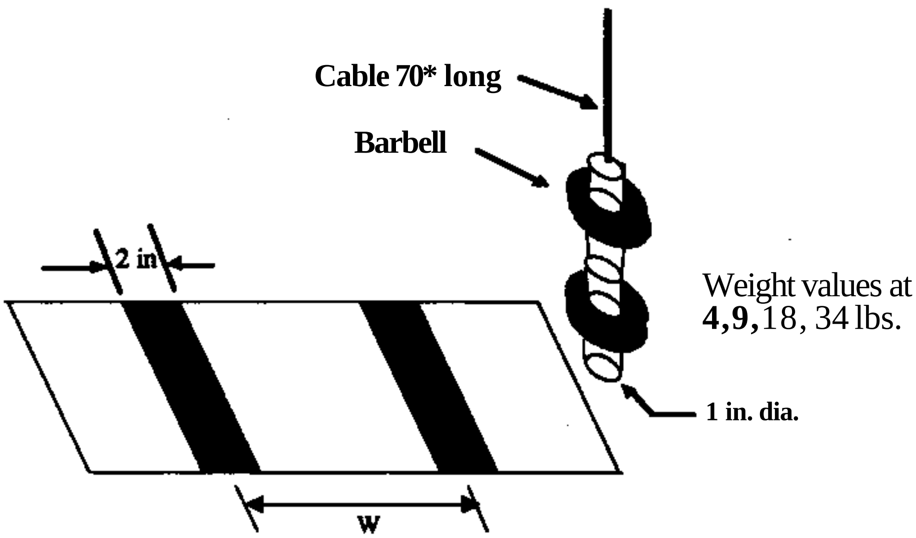

Figure 3. Experiment II Apparatus

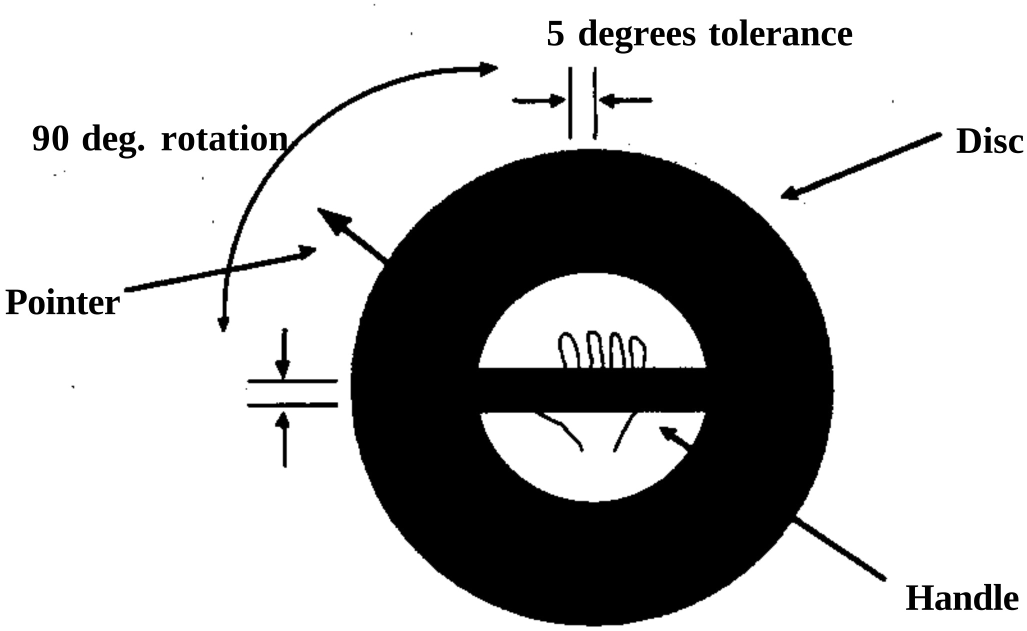

Figure 4. Experiment III Apparatus

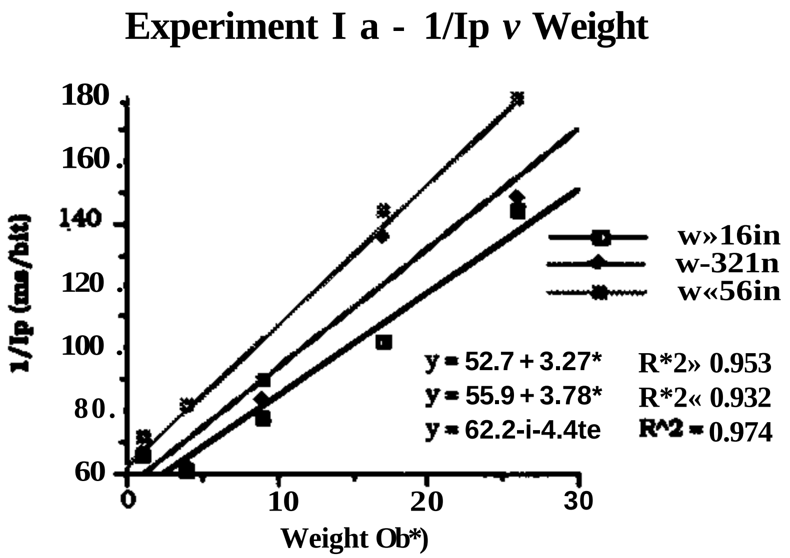

Figure 5. Experiment I a: Gross Motions
Typical Results for one of 3 Subjects

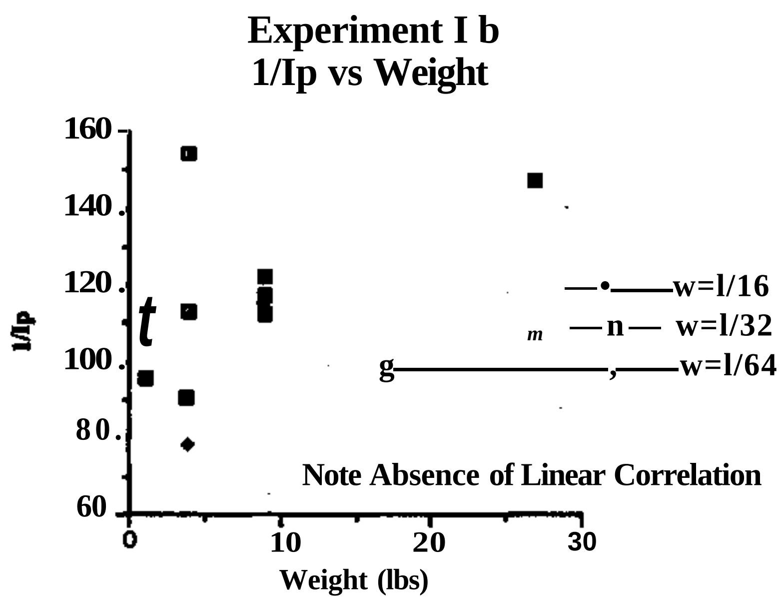

Figure 6. Experiment I b: Fine Motions
Typical Results of one of 3 Subjects

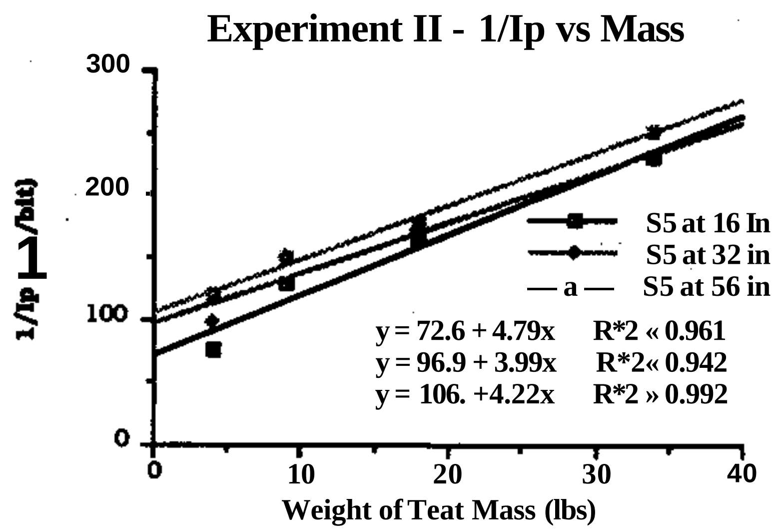

Figure 7. Experiment II
Typical Results of one of 5 Subjects

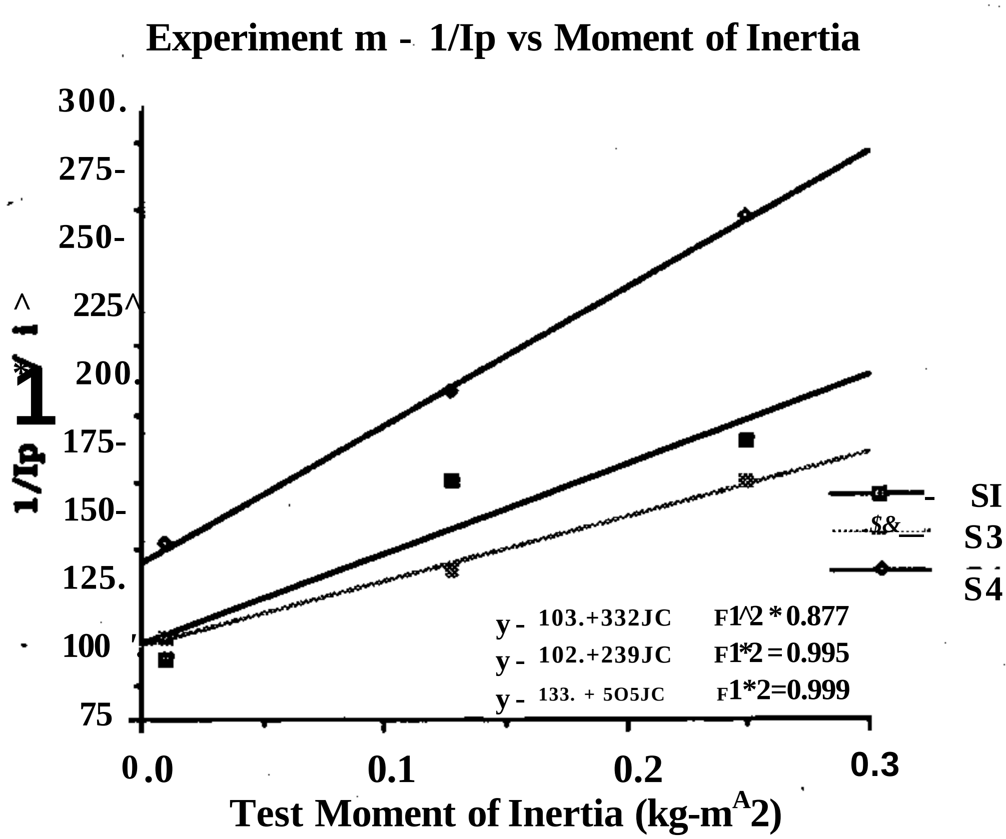

Figure 8. Experiment III
Results by Subject

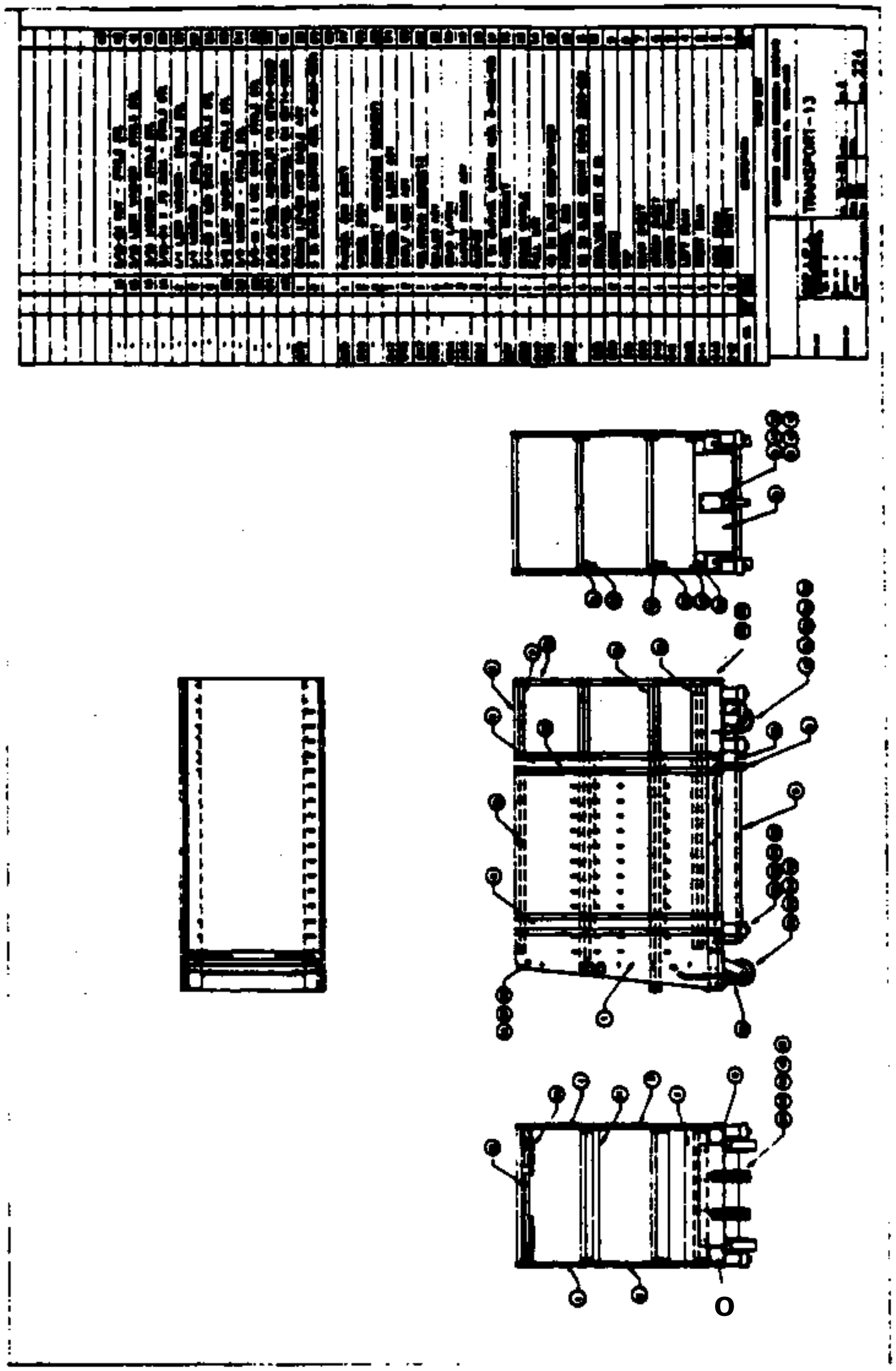

Figure 9. Test Product Design: CMRI Carrier Mail Transporter

Predicted and Actual Assembly Times

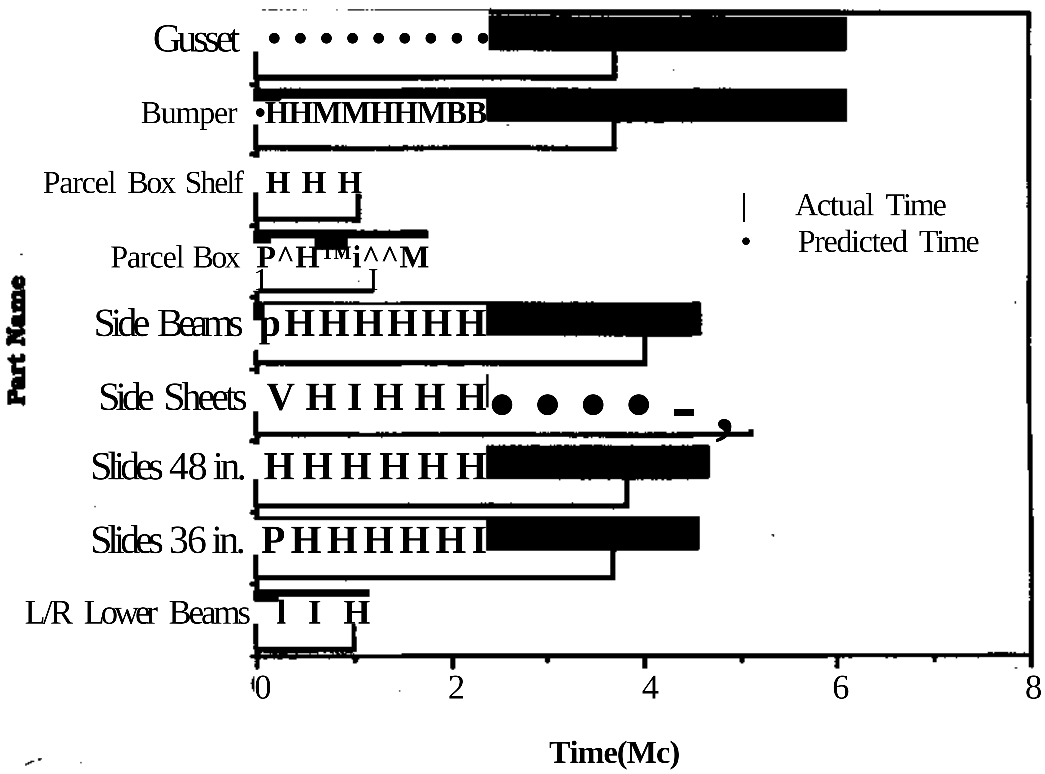

Figure 10. Graph of Predicted vs Actual Times

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