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Robotics and Process Systems Division

CRADA Final Report
for
CRADA Number ORNL95-0338

Improved Design of the Omnidirectional Robotic Platform for Enhancement of Manufacturability and Commercialability

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DEPARTMENT OF ENERGY

ORNL-27 (3-96)

CRADA No. ORNL95-0338
with
Nomadic Technologies, Inc.
for
Improved Design of the Omnidirectional Robotic Platform for Enhancement of Manufacturability and Commercialability

SUMMARY

The purpose of this Cooperative Research and Development Agreement (CRADA), between Oak Ridge National Laboratory (ORNL) and Nomadic Technologies, Inc. has been to produce an improved design of the Omnidirectional Holonomic Platform (OHP) that is easier to manufacture and more suitable for commercialization.

The OHP technology was developed by the ORNL. In 1993, it received an R&D-100 award and in 1994, a patent was accepted by the U.S. Patent Office in final form (#5,374,879).The technology involves a novel wheel system assembly which, through its corresponding control system, can provide rolling platforms with a full omnidirectional motion capability, including simultaneous and independently controlled rotational and translational degrees-of-freedom.

The objective of this project has been to pair ORNL's knowledge of the OHP technology and Nomadic Technologies, Inc.'s experience in manufacturing and market-oriented robotic product development to produce and test an improved design of the OHP. The goal of the project has been to assemble two test-bed platforms based on the improved design. These platforms served as test-beds for engineering tests at ORNL and at Nomadic Technologies, Inc. and were incorporated into two test products of mobile manipulator robotic systems. The test products were submitted to user-acceptance tests at an alpha-customer facility, selected as Stanford University Robotics Laboratory.

The various tests and evaluations of the test products led to implementation of many upgrades in the OHP design, which was concluded to perform well with respect to future manufacturing for various applications. Although Nomadic Technologies, Inc. declined its licensing option of the OHP technology for robotics applications, several parallel activities, cross-fertilizing with this CRADA, were extremely successful. In particular, the OHP technology was licensed by a U.S. company for wheelchair applications.

ORNL P.O.C., François G. Pin, 423-574-6130, pin@ornl.gov

Final Report
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CRADA No. ORNL95-0338
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1. INTRODUCTION

The purpose of this Cooperative Research and Development Agreement (CRADA), between Oak Ridge National Laboratory managed by Lockheed Martin Marietta Energy Research Corp. for the U.S. Department of Energy, and Nomadic Technologies, Inc. has been to produce an improved design of the Omnidirectional Holonomic Platform (OHP) that is easier to manufacture and more suitable for commercialization.

The OHP technology has been developed by the Oak Ridge National Laboratory (ORNL) [1],[2]. The technology involves a novel wheel system assembly which, through its corresponding control system, can provide rolling platforms with a full omnidirectional motion capability, including simultaneous and independently controlled rotational and translational degrees-of-freedom. In 1993, the OHP technology received an R&D-100 award and in 1994, a patent was accepted by the U.S. Patent Office in final form (#5,374,879) [3].

The objective of this project has been to pair ORNL's knowledge of the OHP technology and Nomadic Technologies, Inc.'s experience in manufacturing and market-oriented robotic product development to produce and test an improved design of the OHP. The goal of the project has been to assemble two test-bed platforms based on the improved design. These platforms would serve as test-beds for engineering tests at ORNL and at Nomadic Technologies, Inc. and for incorporation into test products of a mobile manipulator robotic system. The test products would be further submitted to user-acceptance tests through independent evaluations at an alpha-customer facility, selected as Stanford University Robotics Laboratory.

2. APPROACH

To accomplish the objectives of the project, three major tasks were defined, each involving various levels of activities from the partners.

Task 1: Establishment of Requirement for the Improved OHP

In this task the current capabilities of the OHP were reviewed and analyzed. Requirements for improving manufacturability (mechanical and control system), user-friendliness, interfaces, and compatibility with the proposed product were identified. Power requirements and motors adapted to the particular application were also identified.

Task 2: Fabrication and Testing of the Improved OHP

A new design incorporating all the improvements identified in Task 1 was developed and blueprints of this improved design were generated. Two new platforms were fabricated and engineering tests were performed.

Task 3: Incorporation of the Improved OHP in the Test Product

The improved platform technologies were incorporated into the proposed mobile manipulator robotic system test product and user- and market-acceptance studies were performed at Stanford University Robotics Laboratory.

3. MAJOR RESULTS

3.1. Design Improvements

Several design needs and improvements were identified during the review and analysis of the OHP and corresponding modifications were implemented as follows:

1. *Alignment of the ball within the yoke and proper bearing pre-load.*

   A mechanism was added to adjust the position of the ball's tapered roller bearing cone to precisely position the ball within the yoke and set the proper pre-load for the bearings. The mechanism consists of a threaded collar on the ball shaft that is rotated to adjust the position. Each ball has two adjustable collars such that the pre-load and alignment can be set independently. A set screw mechanism is used to lock the adjustments in place.

2. *Improved yoke strength.*

   The yoke is now machined from a continuous piece of steel. This eliminates the weak spots caused by the previous screw fasteners.

3. *Improved attachment of the ball shaft.*

   The method for attaching the shaft to the yoke has been re-designed to make a wider attachment area that distributes the forces over a wider contact area. Strength and rigidity are improved. The tolerances of the mechanism are specified such that no adjustment mechanism is needed when fitting the shaft to the yoke.

4. *Simpler alignment of the gear train.*

   The shaft for the gears now have key slots carefully placed in the proper position such that no alignment is necessary after assembly.

5. *Access holes for motor alignment fasteners.*

   Access holes have been added so that the bolts holding the motor could be loosened to change the motor/gear alignment.

6. *Changed position for wheel pod fasteners.*

   The bolts that attach the wheel pods to the vehicle chassis have been re-located such that they can be accessed from underneath the vehicle.

7. *Thicker rubber coating on the balls.*

   The dimensions of the balls were changed to allow thicker rubber for improved wear, softer ride, and more traction.

3.2. Blueprints and Mobile Manipulator Test Product

Based on the above design improvements, a set of revised drawings was generated for the basic OHP technology sized for application to the test product. These blueprints are shown in Appendix A. Two OHP platforms were then developed for incorporation into the proposed test product shown in Fig. 1.

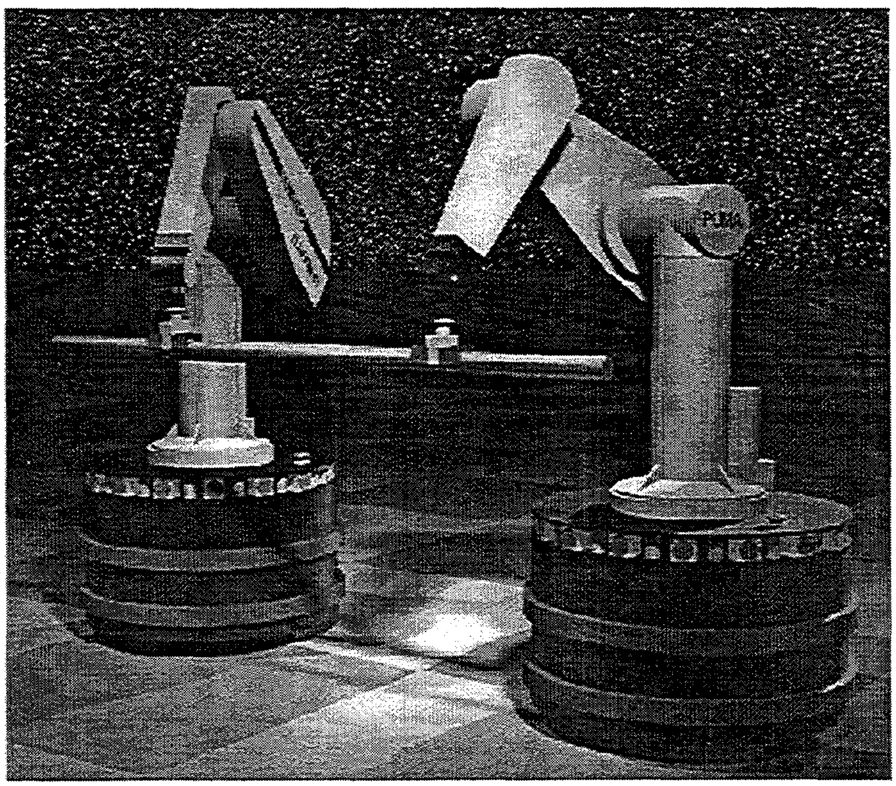


Fig. 1. The two proposed mobile manipulator test products incorporating the OHP technology.

3.3. User-Acceptance Tests and Evaluations

In addition to the successful evaluation of the improvements listed in Section 3.1, the evaluation of the test platforms by the Alpha Customer, Stanford University, led to the recommendation to increase the torques provided to the wheels. This was accomplished on the test platforms by modifying the transmission ratios of the external gears that transmit motor torque to the wheels and coordinate the motion of the wheels in each assembly.

The enhanced test products, nicknamed Romeo and Juliet, have been extensively used at the Stanford University Robotics Laboratory [4]. In particular, the platforms' holonomy permitted several experiments in multi-mobile manipulators holding common objects to be performed that otherwise would not have been feasible.

4. CONCLUSION AND SPIN-OFF

At the conclusion of the CRADA activities, Nomadic Technologies, Inc., evaluated their option for licensing the OHP technology for their family of mobile robot products. They elected to decline their licensing option, mostly on the basis of a non-favorable Cost Benefit Analysis including the licensing costs.

From a technical point of view and other licensing activities, this CRADA was extremely successful in its intended outcome of improving the OHP design toward manufacturability and durability for various applications. Parallel developments, which cross-fertilized with this CRADA, led to the licensing, in 1996, of the OHP technology to Cybertrax, Inc., a Florida-based company, for wheelchair application. The prototype wheelchair, completed in early 1997 is shown in Fig. 2. This prototype wheelchair was the main demonstration feature of the OHP technology that was selected as a 1997 Discover Magazine Award Finalist. Some of the announcement of this selection and text extracted from *Discover* magazine are shown in Appendix B.

5. REFERENCES

[1] Pin, F. G. and S. M. Killough, "A New Family of Omnidirectional and Holonomic Wheeled Platforms for Mobile Robots," *IEEE Transactions on Robotics and Automation* **10**(4), 480–489 (1994).

[2] Killough, S. M. and F. G. Pin, "Design of an Omnidirectional and Holonomic Wheeled Platform Prototype." In Proceedings of the 1992 IEEE International Conference on Robotics and Automation, Nice, France, May 10–15, 1992, 84–90.

[3] Pin, F. G. and S. M. Killough, "Omni-Directional and Holonomic Rolling Platform with Decoupled Rotational and Translational Degrees-of-Freedom," U.S. Patent #5,374,879, *Official Gazette*, 1808 (December 20, 1994).

[4] Khatib, O. et al., *Cooperative Tasks in Multiple Mobile Manipulation Systems*, pp. 345–350 in "Robotics and Manufacturing: Recent Trends in Research and Applications" Vol. 6, Eds. M. Jamshidi, F. G. Pin, and P. Dauchez, ASME Press, New York, 1996.

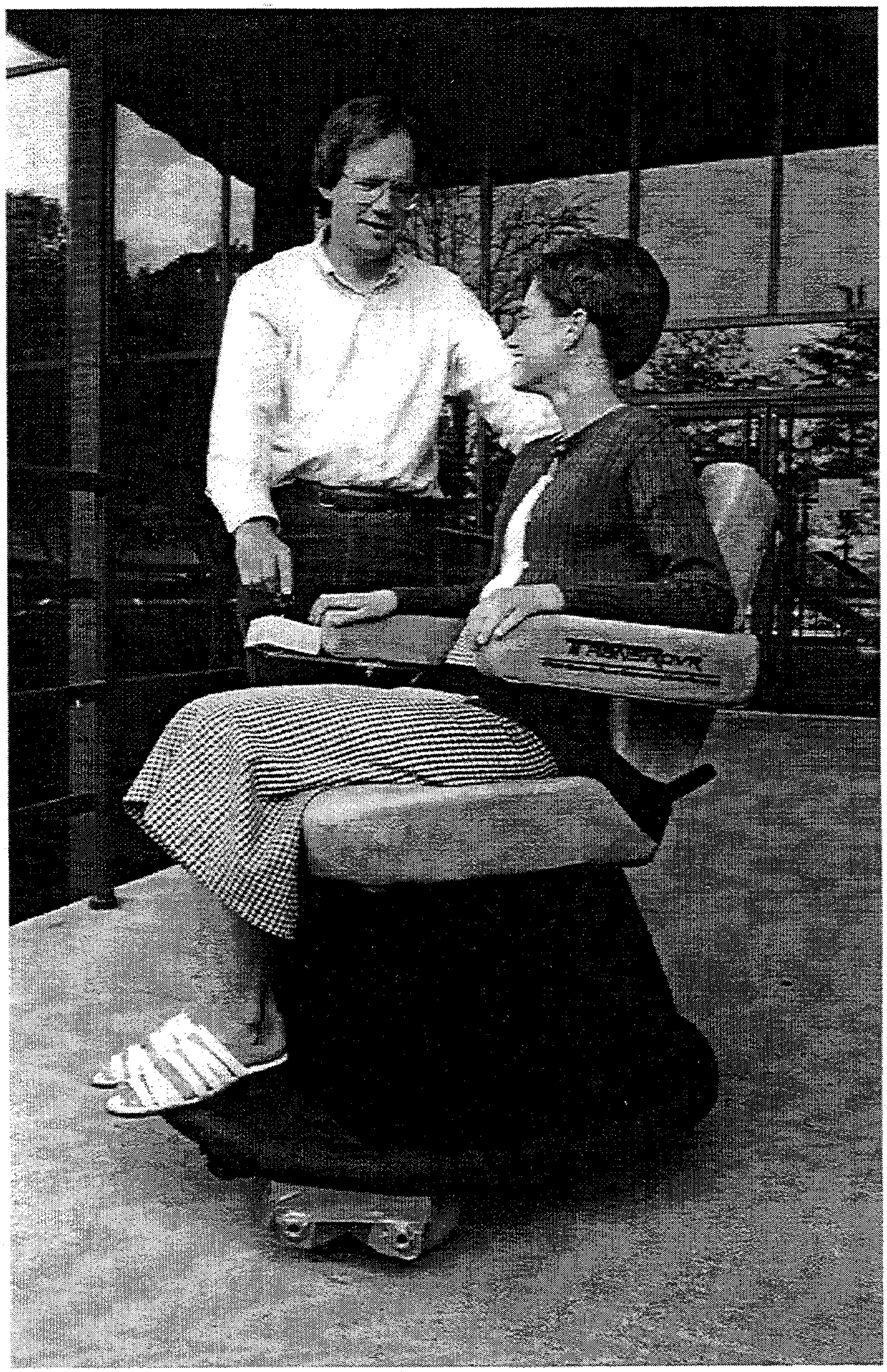
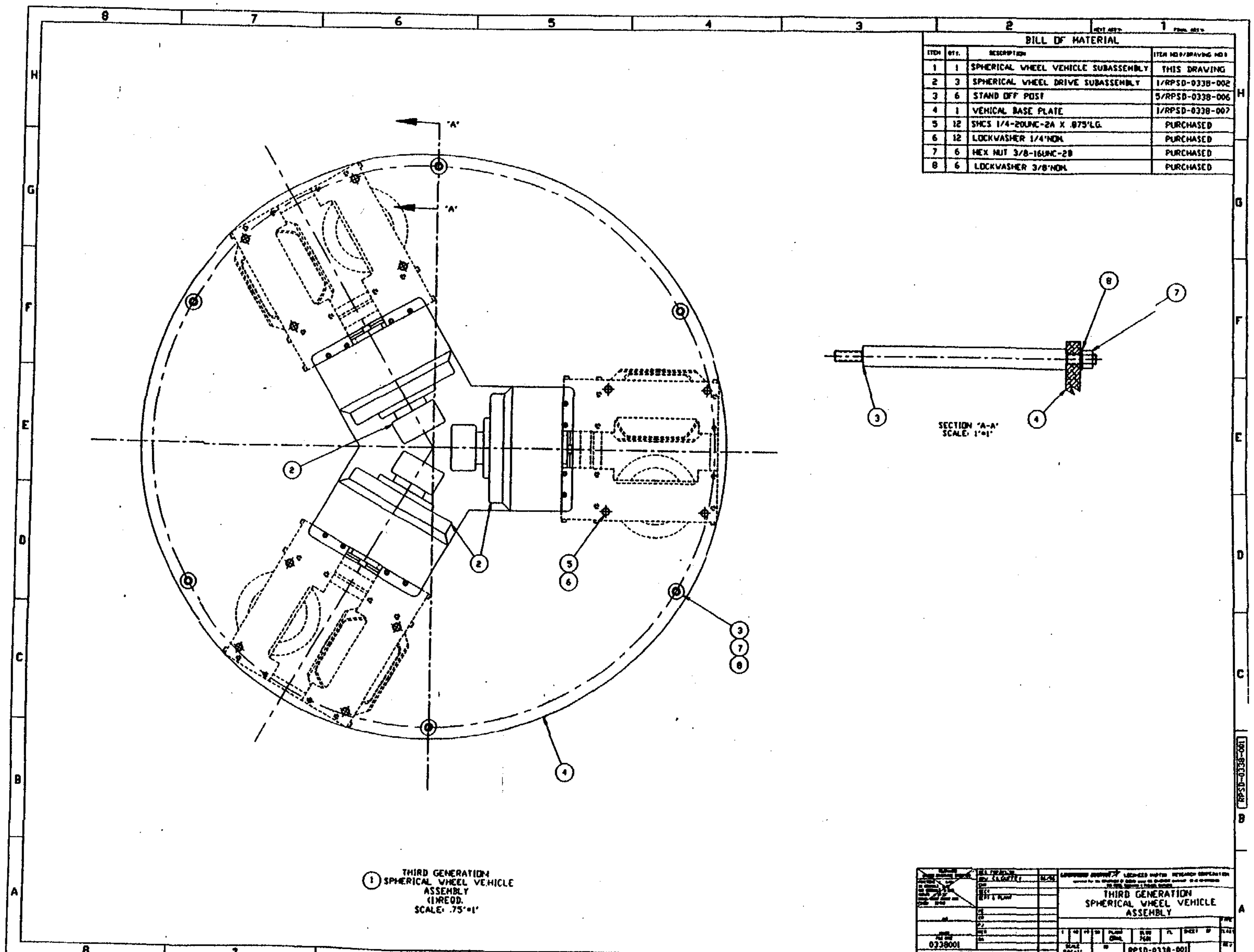


Fig. 2. Cybertrax, Inc., "Transrovr" prototype wheelchair using the OHP technology.

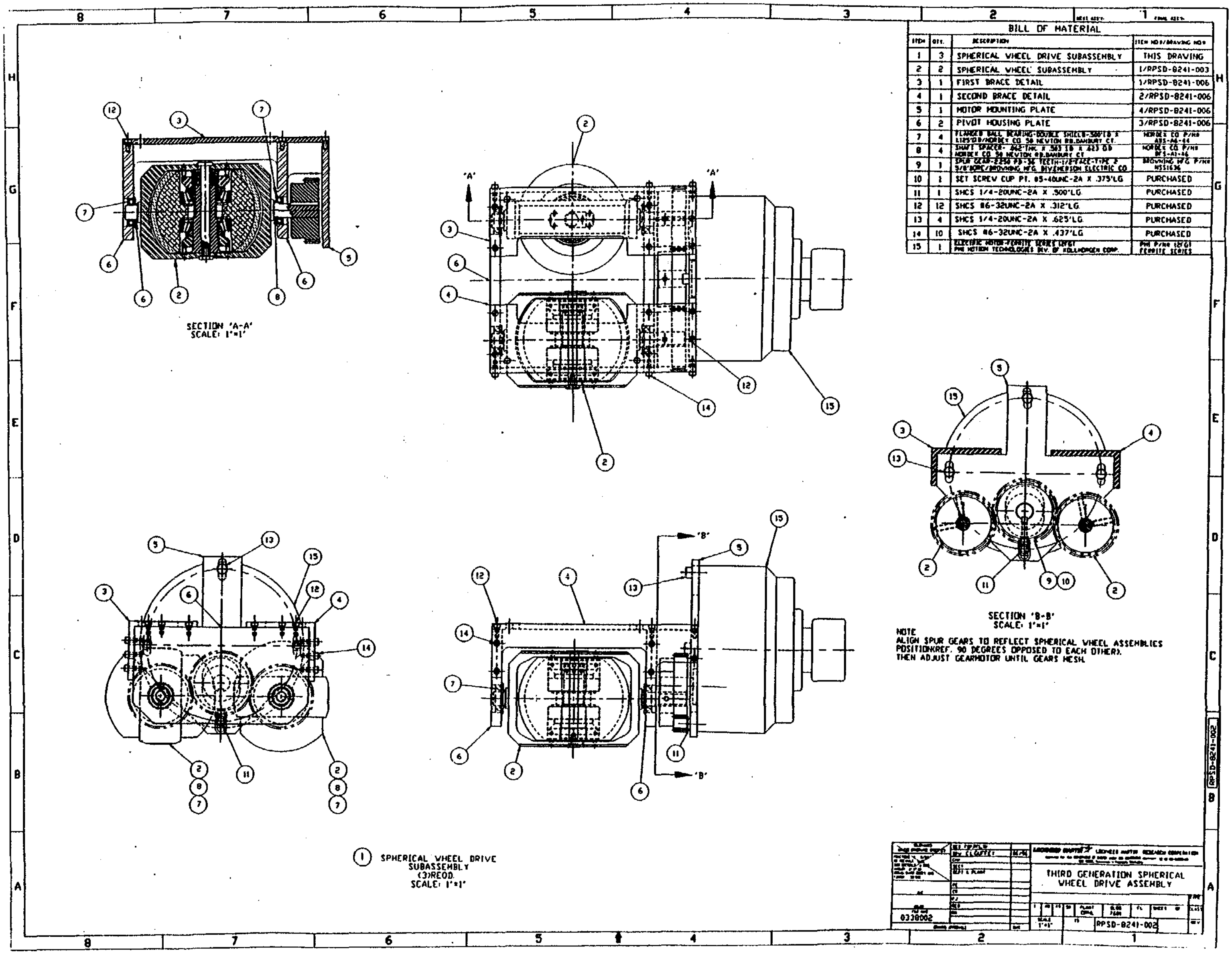
APPENDIX A

BLUEPRINTS OF THE IMPROVED OHP DESIGN



BILL OF MATERIAL

ITEM	QTY.	DESCRIPTION	ITEM NO./DRAWING NO.
1	1	SPHERICAL WHEEL VEHICLE SUBASSEMBLY	THIS DRAWING
2	3	SPHERICAL WHEEL DRIVE SUBASSEMBLY	1/RPSD-0338-002
3	6	STAND OFF POST	5/RPSD-0338-006
4	1	VEHICAL BASE PLATE	1/RPSD-0338-007
5	12	SHCS 1/4-20UNC-2A X .875"LG.	PURCHASED
6	12	LOCKWASHER 1/4"NOM.	PURCHASED
7	6	HEX NUT 3/8-16UNC-2B	PURCHASED
8	6	LOCKWASHER 3/8"NOM.	PURCHASED



BILL OF MATERIAL

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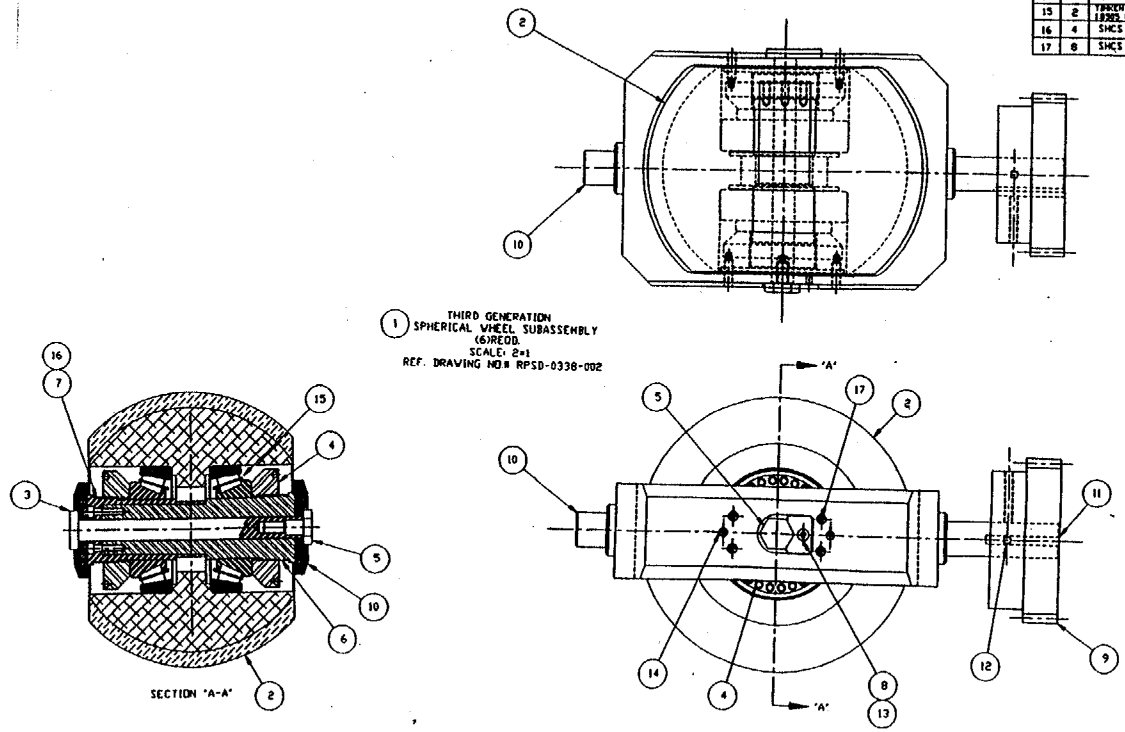
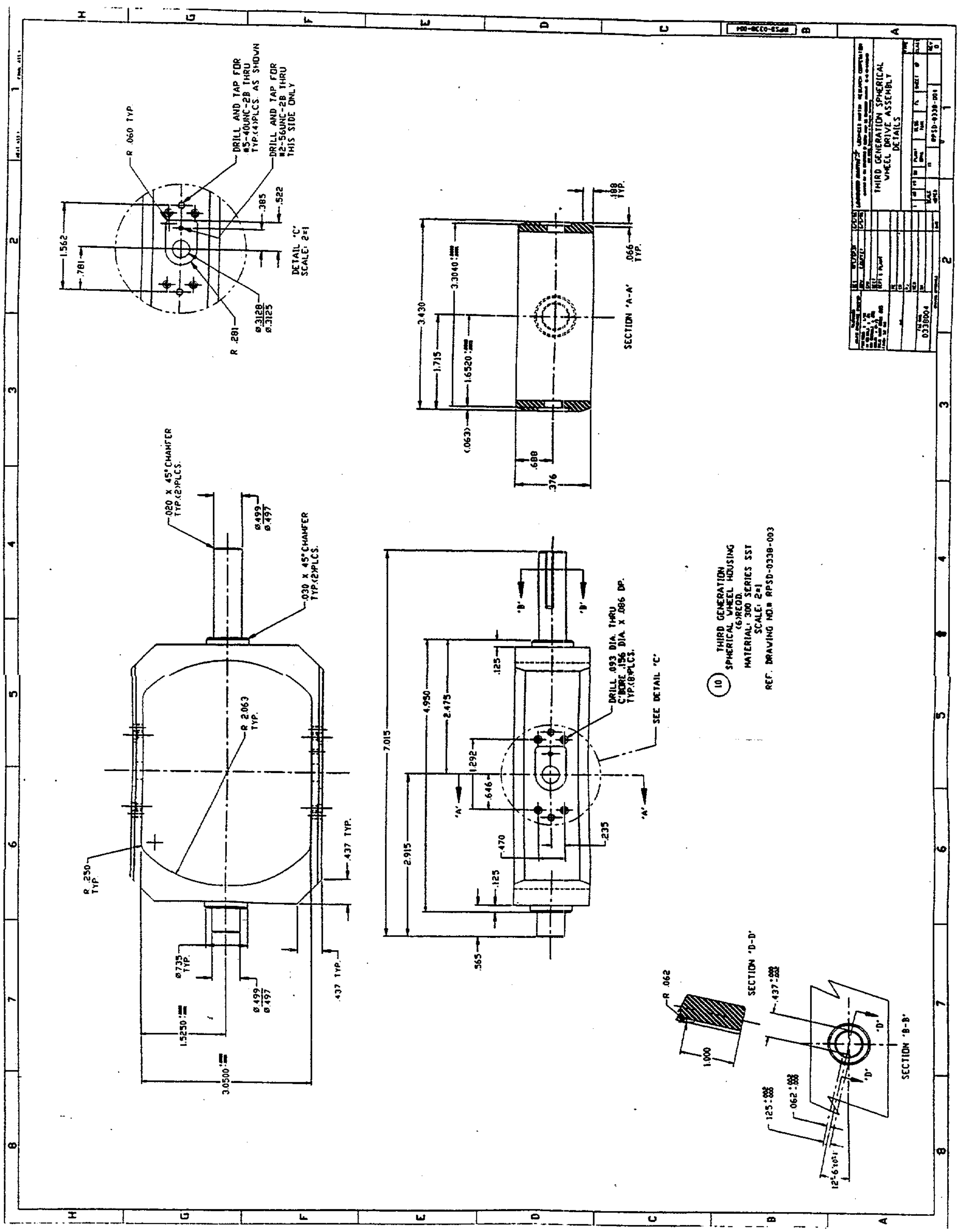
1	3	SPHERICAL WHEEL DRIVE SUBASSEMBLY	THIS DRAWING
2	2	SPHERICAL WHEEL SUBASSEMBLY	1/RPSD-8241-003
3	1	FIRST BRACE DETAIL	1/RPSD-8241-006
4	1	SECOND BRACE DETAIL	2/RPSD-8241-006
5	1	MOTOR MOUNTING PLATE	4/RPSD-8241-006
6	2	PIVOT HOUSING PLATE	3/RPSD-8241-006
7	4	FLANGED BALL BEARING-DOUBLE SHIELD-.500"ID X 1.125"OD/NORDEX CO 50 NEWTON RD.DANBURY CT.	NORDEX CO P/N ABS-A6-44
8	4	SHAFT SPACER- .062"THK X .503 ID X .623 OD NORDEX CO 50 NEWTON RD.DANBURY CT	NORDEX CO P/N BFS-A1-46
9	1	SPUR GEAR-.2250 PD-36 TEETH-1/8"FACE-TYPE 2 3/8"BORE/BROWNING MFG. DIV.EMERSON ELECTRIC CO	BROWNING MFG P/N NSS1636
10	1	SET SCREW CUP PT. #5-40UNC-2A X .375"LG	PURCHASED
11	1	SHCS 1/4-20UNC-2A X .500"LG	PURCHASED
12	12	SHCS #6-32UNC-2A X .312"LG	PURCHASED
13	4	SHCS 1/4-20UNC-2A X .625"LG	PURCHASED
14	10	SHCS #6-32UNC-2A X .437"LG	PURCHASED
15	1	ELECTRIC MOTOR-FERRITE SERIES 12FG1 PMI MOTION TECHNOLOGIES DIV. OF KOLLMORGEN CORP.	PMI P/N 12FG1 FERRITE SERIES

BILL OF MATERIAL			
ITEM	QTY.	DESCRIPTION	ITEM NO./DRAWING NO.
1	6	SPHERICAL WHEEL SUBASSEMBLY	THIS DRAWING
2	1	SPHERICAL WHEEL DETAIL	2/RPSD-0338-005
3	1	MAIN AXEL DETAIL	3/RPSD-0338-005
4	2	BEARING ADJUSTMENT RETAINER	4/RPSD-0338-005
5	1	AXEL FASTENER DETAIL	5/RPSD-0338-005
6	1	INNER BEARING SLEEVE	6/RPSD-0338-008
7	1	OUTER BEARING SLEEVE	7/RPSD-0338-008
8	1	AXEL BOLT KEEPER	8/RPSD-0338-008
9	1	DRIVE GEAR DETAIL	9/RPSD-0338-008
10	1	SPHERICAL WHEEL HOUSING	10/RPSD-0338-004
11	1	.125 X .125 X 1.00LG KEY	KEY STK.
12	2	SET SCR. #3-40UNC-2A X .375"LG. CUP POINT	PURCHASED
13	1	BUTTON HD. SCR. #2-56UNC-2A X .187"LG.	PURCHASED
14	10	SET SCR. #3-40UNC-2A X .438"LG. FULL DOG	PURCHASED
15	2	TIMKEN TAPERED ROLLER BEARING-.390 BORE 1.0385 O.D. DIXIE BEARING CO. VENDOR	CUP P/N LM72810 CONE P/N LM72849
16	4	SHCS #2-56UNC-2A X .437"LG.	PURCHASED
17	8	SHCS #2-56UNC-2A X .375"LG.	PURCHASED





THIRD GENERATION SPHERICAL WHEEL DRIVE ASSEMBLY DETAILS
THIRD GENERATION SPHERICAL WHEEL HOUSING (6)REQD.
MATERIAL: 300 SERIES SST
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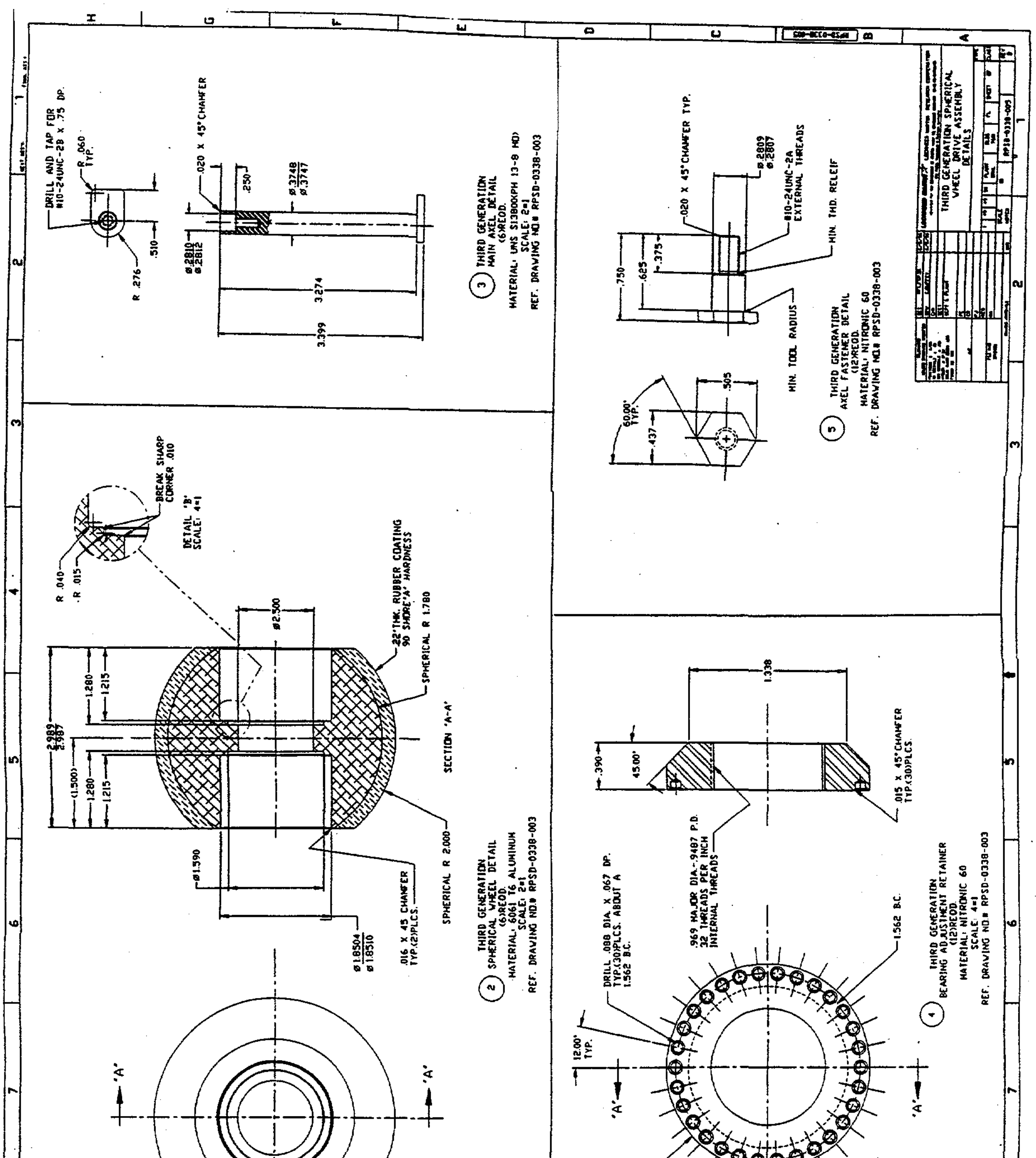
REF. DRAWING NO.# RPSD-0338-003
DRILL AND TAP FOR #5-40UNC-2B THRU TYP.(4)PLCS AS SHOWN
DRILL AND TAP FOR #2-56UNC-2B THRU THIS SIDE ONLY
DETAIL 'C' SCALE: 2=1
SECTION 'A-A'
SECTION 'B-B'
SECTION 'D-D'
SEE DETAIL 'C'
DRILL .093 DIA. THRU C'BORE .156 DIA. X .086 DP. TYP.(8)PLCS.
.020 X 45° CHAMFER TYP.(2)PLCS.
.030 X 45° CHAMFER TYP.(2)PLCS.
R 2.063 TYP.
R .250 TYP
R .060 TYP
R .281
R .062
.437 TYP.


THIRD GENERATION
MAIN AXEL DETAIL
(6)REQD.
MATERIAL: UNS S13800(PH 13-8 MO)
SCALE: 2=1
REF. DRAWING NO# RPSD-0338-003
THIRD GENERATION
AXEL FASTENER DETAIL
(12)REQD.
MATERIAL: NITRONIC 60
REF. DRAWING NO# RPSD-0338-003
THIRD GENERATION
SPHERICAL WHEEL DETAIL
(6)REQD.
MATERIAL: 6061 T6 ALUMINUM
SCALE: 2=1
REF. DRAWING NO# RPSD-0338-003
THIRD GENERATION
BEARING ADJUSTMENT RETAINER
(12)REQD.
MATERIAL: NITRONIC 60
SCALE: 4=1
REF. DRAWING NO# RPSD-0338-003
SECTION 'A-A'
DETAIL 'B'
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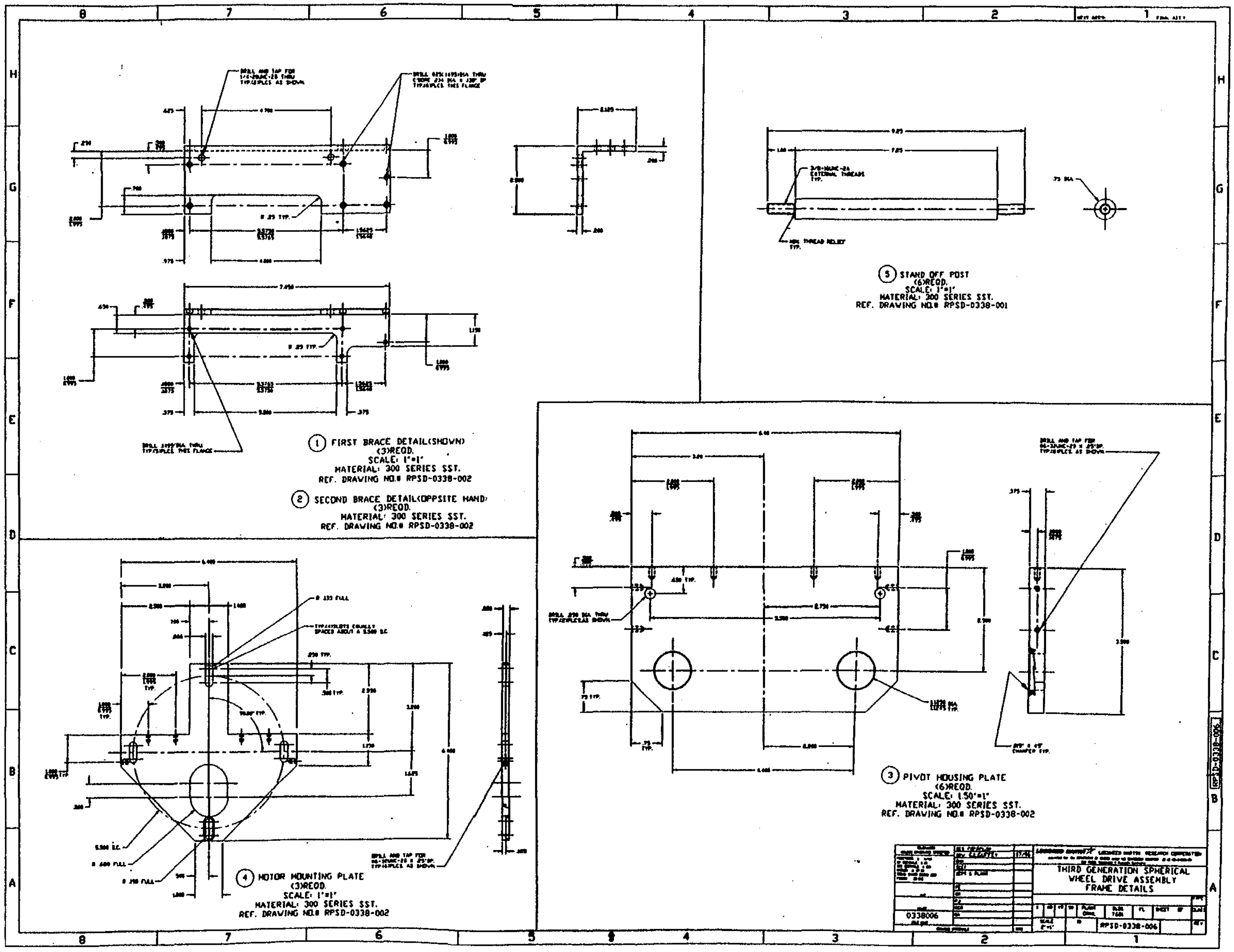
THIRD GENERATION SPHERICAL
WHEEL DRIVE ASSEMBLY
DETAILS



1 FIRST BRACE DETAIL(SHOWN)
(3)REQD.
SCALE: 1"=1"
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REF. DRAWING NO.# RPSD-0338-002
2 SECOND BRACE DETAIL(OPPSITE HAND)
(3)REQD.
MATERIAL: 300 SERIES SST.
REF. DRAWING NO.# RPSD-0338-002
5 STAND OFF POST
(6)REQD.
SCALE: 1"=1"
MATERIAL: 300 SERIES SST.
REF. DRAWING NO.# RPSD-0338-001
3 PIVOT HOUSING PLATE
(6)REQD.
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4 MOTOR MOUNTING PLATE
(3)REQD.
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FRAME DETAILS
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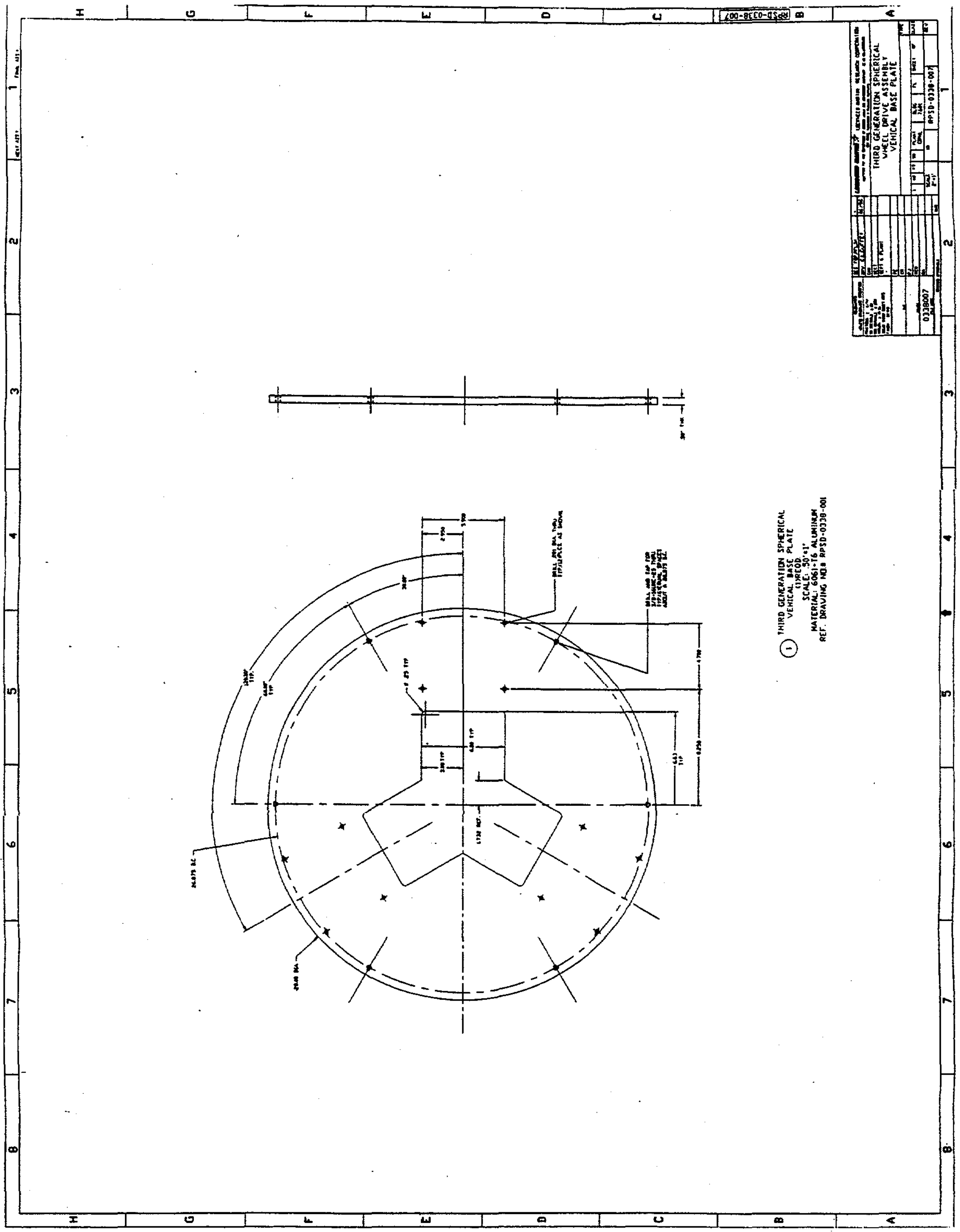
THIRD GENERATION SPHERICAL
WHEEL DRIVE ASSEMBLY
VEHICAL BASE PLATE
RPSD-0338-007
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(1)REQD
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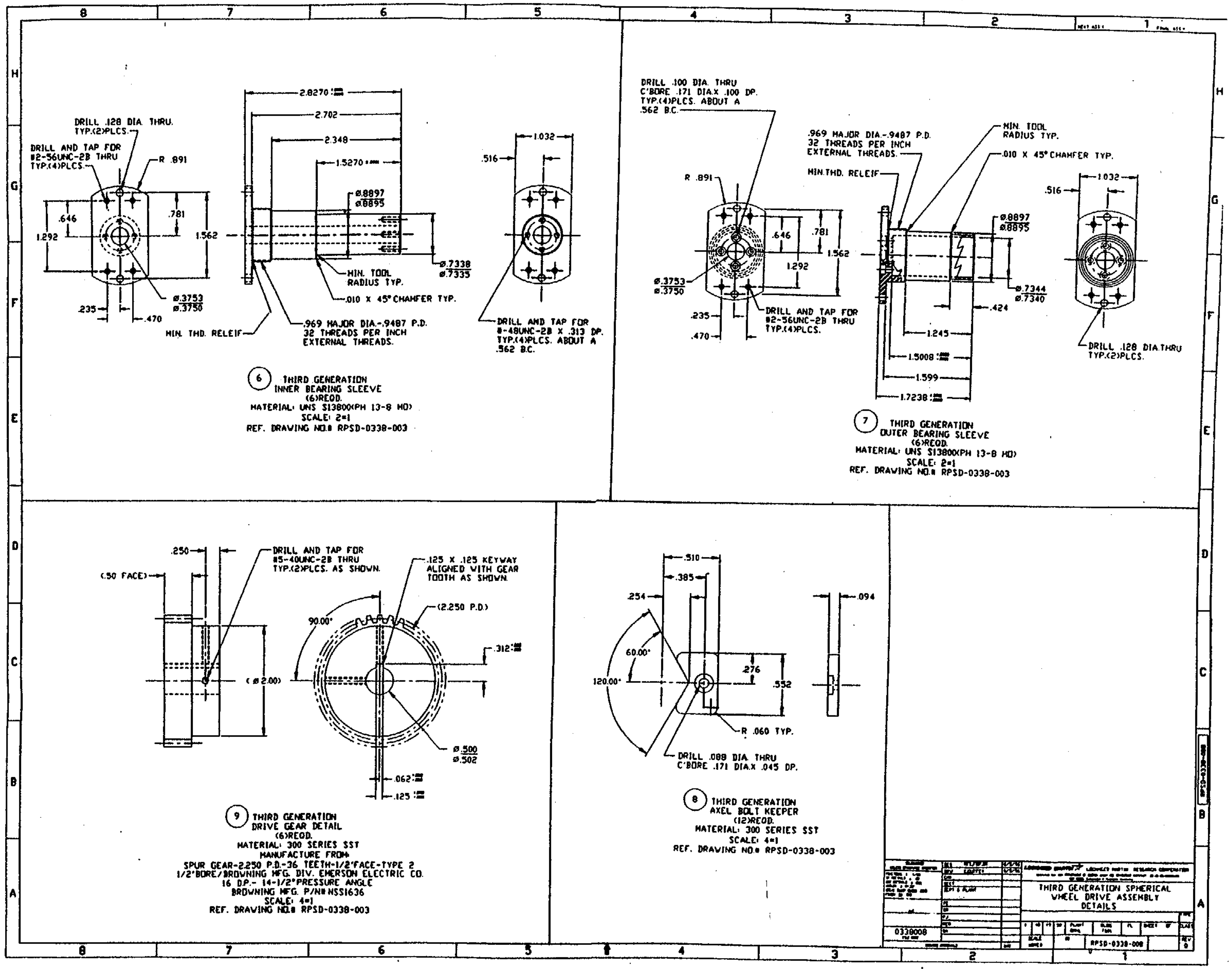
DRILL .128 DIA THRU. TYP.(2)PLCS.
DRILL AND TAP FOR #2-56UNC-2B THRU TYP.(4)PLCS.
R .891
MIN. THD. RELEIF
.969 MAJOR DIA-.9487 P.D. 32 THREADS PER INCH EXTERNAL THREADS.
MIN. TOOL RADIUS TYP.
.010 X 45° CHAMFER TYP.
DRILL AND TAP FOR #-48UNC-2B X .313 DP. TYP.(4)PLCS. ABOUT A .562 B.C.
6 THIRD GENERATION INNER BEARING SLEEVE (6)REQD.
MATERIAL: UNS S13800(PH 13-8 MO)
SCALE: 2=1
REF. DRAWING NO.# RPSD-0338-003
DRILL .100 DIA. THRU C'BORE .171 DIA.X .100 DP. TYP.(4)PLCS. ABOUT A .562 B.C.
DRILL AND TAP FOR #2-56UNC-2B THRU TYP.(4)PLCS.
DRILL .128 DIA.THRU TYP.(2)PLCS.
7 THIRD GENERATION OUTER BEARING SLEEVE (6)REQD.
MATERIAL: UNS S13800(PH 13-8 MO)
SCALE: 2=1
REF. DRAWING NO.# RPSD-0338-003
(.50 FACE)
DRILL AND TAP FOR #5-40UNC-2B THRU TYP.(2)PLCS. AS SHOWN.
.125 X .125 KEYWAY ALIGNED WITH GEAR TOOTH AS SHOWN.
(2.250 P.D.)
9 THIRD GENERATION DRIVE GEAR DETAIL (6)REQD.
MATERIAL: 300 SERIES SST
MANUFACTURE FROM:
SPUR GEAR-2.250 P.D.-36 TEETH-1/2"FACE-TYPE 2
1/2"BORE/BROWNING MFG. DIV. EMERSON ELECTRIC CO.
16 D.P.- 14-1/2°PRESSURE ANGLE
BROWNING MFG. P/N# NSS1636
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R .060 TYP.
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8 THIRD GENERATION AXEL BOLT KEEPER (12)REQD.
MATERIAL: 300 SERIES SST
SCALE: 4=1
REF. DRAWING NO.# RPSD-0338-003
THIRD GENERATION SPHERICAL WHEEL DRIVE ASSEMBLY DETAILS
RPSD-0338-000

APPENDIX B

ANNOUNCEMENT AND TEXT RELATED TO THE 1997 DISCOVER AWARD FINALISTS SELECTION

Discover Awards 1997 Finalists

Discover
THE WORLD OF SCIENCE
MAGAZINE

AUTOMOTIVE & TRANSPORTATION

TURN AND PIVOT ON THREE

Omnidirectional Vehicle Platform

Stephen Killough

Oak Ridge National Laboratory

For years, engineers have tried in vain to produce wheelchairs and loading vehicles that can swivel and slide into tight spaces, like an office chair on casters. Nothing worked--until Killough's bizarre design gave it a whirl. A computer controls three pairs of perpendicularly arranged, variable-speed balloon wheels, so that at least one wheel of each pair touches the ground at any one time. The design is now being incorporated into motorized wheelchairs and bomb-loaders for fighter jets.

TURN AND PIVOT ON THREE

Oak Ridge National Laboratory's Omnidirectional Platform

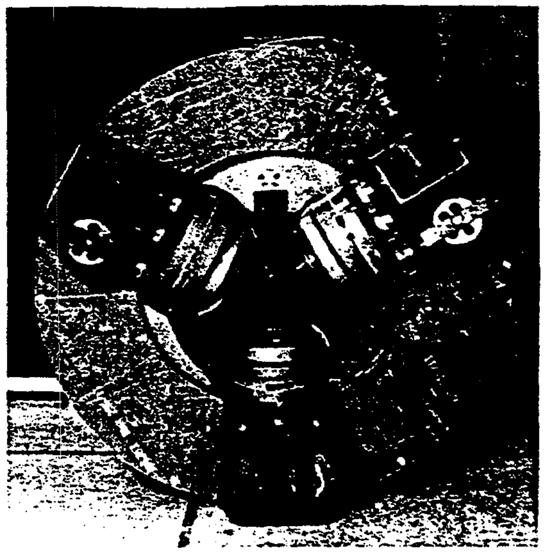
INNOVATOR: STEPHEN KILLOUGH

Anyone who struggles to master parallel parking knows a plague as old as the ox-cart: our glorious wheeled vehicles are hellish to maneuver in tight spaces. This mechanical glitch costs us dearly. Watch a forklift backing and forthing in a warehouse, or a wheelchair zigzagging through a twisted corridor and you'll see magnificent examples of wasted motion. When Stephen Killough, a robotics engineer at Oak Ridge National Laboratory, saw the ancient curse in wheeled robots too, he came up with a solution that is technically sweet, mathematically elegant, and visually discombobulating.

His reasoning started with a simple question: Why couldn't a car simply pivot like an office chair on casters and slide sideways into a parking spot? Because, he knew, you'd need a minimum of three casterlike wheels on the floor, and each would require two motors: one to drive its rotation and another to make it pivot. Six motors would be too unwieldy, complex, and expensive. According to engineering principles, Killough realized, you should be able to manage with only three independent motors, but nobody had been able to figure out how. Killough looked at the ideas other inventors had tried, including little rollers embedded around the rim of a bigger wheel, allowing it to roll sideways, but they were all flawed in some critical way. While playing around with such embedded rotations, however, he discovered an ideal arrangement.

Picture a round platform with three motors underneath, each governing the motion of two wheels that look like miniature balloon tires. The wheels in each pair are mounted in a cage at right angles to each other; the motor can rotate the cage so that one wheel or the other is touching the ground at any one time. By configuring the three pairs of wheels to allow the same type of motion found in three pivoting casters, and by changing the relative speeds of the motors, Killough can make his robotic platform rotate, follow a straight or curved path, and even rotate while moving forward.

After Killough nailed the mechanical design, François Pin helped him control the complicated choreography of the wheels with a computer. There is nothing intuitively obvious about the arrangement they must assume. "It's almost like you have to trust the mathematics that says it should work," says Killough. "It's bizarre to watch. It flabbergasts everybody. It's like a taffy-puller machine." In 1994 Killough and Pin readied their first public demonstration: they strapped a pen to their robot and wrote cursive letters on the floor. This fluent mobility led to a partnership in January 1996 with Cybertrax Innovative Technologies, a start-up company in Tampa developing a new motorized wheelchair. The U.S. Air Force will also try out the platform to load bombs onto fighter jets. But a forklift manufacturer that sent people to look at it isn't convinced. "Customer acceptance," Killough reckons, "is going to make or break this product."



WHEELS ONLY A MATHEMATICIAN COULD APPRECIATE.

Top: Courtesy General Motors; bottom: courtesy Lawrence Livermore National Laboratory

Courtesy Oak Ridge National Laboratory

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