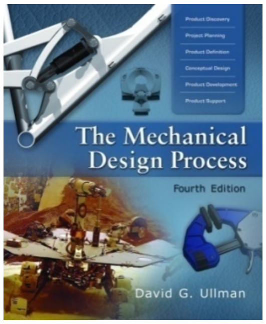
Unsticking a Concept at **MAGIC**WHEELS



A Case Study for *The Mechanical Design Process*

Introduction

Wheelchairs work well on flat, level surfaces, but on inclines and soft surfaces they can be impossible or even dangerous. Wheelchair users refer to this problem as being in “flat-jail”. In 1996 Steve Meginnis set out to resolve this limitation. Steve already had a background in developing products with nearly 40 years of experience designing and developing medical and aircraft products, He holds over 20 patents and was the mechanical engineer who developed the 1st Sonicare ® toothbrush. He considers solving hard mechanical problems a challenge and the development of a wheelchair wheel that could do more than move on a flat, level surface pushed even his capabilities.

Traditional wheelchairs are propelled by pushing on a hand rim which is attached directly to each wheel. The rider pushes, releases, re-grabs the rim, and pushes again. The challenge in negotiating hills and other not-so-nice surfaces is to develop a mechanism that can gear down the tangential force put into the hand rim. This seems simple – cars, bicycles and other devices have had transmissions for over a hundred years. However, when a wheelchair is powered by cyclical arm pushes, especially by people with limited strength and mobility, it is not so simple.

Figure 1 A wheelchair with MAGICWheels going up a hill

MAGICWHEELS® tackled this problem and developed a 2-speed, patented system that has met with wide acceptance. During the development, there were several times when the design got stuck and mechanical problems had to be overcome with clever changes. In this case study, we explore methods to help overcome design sticking points.

- **The Problem**: **MAGIC**WHEELS was running out of time and their product could not be shifted with one hand – a customer requirement.
- **The Method**: Techniques useful to overcome stuck design problems.
- **Advantages/Disadvantages:** These methods take work, but they can help un-stick hard design problems.


Figure 2: Pushing on the hand rim and details of a MAGICWheels 2-gear wheel

Traditional wheelchairs are propelled by grasping the hand rim as shown in Figures 1 and 2. This gives a 1-to-1 gear ratio between the motion of the hand and the rotation of the wheel. In order to gain more torque - needed to go up a hill - the wheelchair user has only one option and that is to apply more force to the hand rim. This puts high stress and strain on the shoulder and arm joints and muscles, often causing severe repetitive motion injury. Many wheelchair users are limited in the amount of force they can apply due to their physical abilities. Additionally, if part way up a grade and the hand rims are released, the chair will roll back down the hill.

This is not a new problem. The first multi speed wheelchair was patented over fifty years ago and there have been many since, but none have made it into commercial use until **MAGIC**WHEELS. Before exploring solutions to this problem and how Steve and **MAGIC**WHEELS resolved the issue, the problem needs to be better understood and the set of customers' requirements discussed.

Customers Requirements

In developing the customers' requirements, the first question that needs to be answered is "Who are the customers?" (see Chapter 6 in *The Mechanical Design Process*). The primary customers are paraplegics, quadriplegics and other disabled persons who use wheelchairs to get around. Beyond these primary customers, insurance companies, Medicare/Medicaid and the Veterans Administration are important as they pay for most mobility aids and accessories.

What Steve wanted to develop was the ability to operate a wheelchair on hills and other uneven terrain. Ideally a wheelchair should be able do the following sequence of events:

- Cruise on a level surface as with a traditional wheelchair
- Shift into a lower gear when approaching a hill easily
- Negotiate the hill with no more shoulder load than when on flat ground.
- Hold its position when the hand rim is released going up the hill
- Easily shift back into cruise when cresting the hill
- Assist in braking when going downhill, so it can't run away.

These translate into the following engineering requirements:

- 1:1 gear ratio through hand rim for normal use

Any geared wheel system must behave like a traditional wheelchair when on a flat surface which is at least 95% of the time. It must be virtually invisible (functionally) to the user until shifted to the lower gear when needed.

- Take load off arms and shoulders for climbing hills, going up ramps, etc
  This requires sufficient gearing to climb 5% grade with same or lower force as on a level ground in 1:1 gear. A maximum grade of 5% is the American with Disabilities Act (ADA) requirement. (**MAGIC**WHEELS advertises 10% and actually tests on 15%).
- Easy, one-handed shifting between gears
  Shifting should be with similar motions as is propulsion to ensure rapid transition between gears. Since the two wheels are independent, shifting must be with one hand for each wheel.
- No roll back – must automatically hold when climbing hills
  When climbing hills it is important that the wheelchair hold its position between power thrusts on the hand rim and not require any other action to hold position if the user pauses.
- Minimal “windage” – low or no increase in drag due to gearing that is not in use. When in direct drive (1:1) there must be no drag due to low ratio gears and conversely, when in low gear no energy should be wasted on the 1:1 ratio.
- Downhill control
  If the product is to go up-hill, it must also help in going downhill. On many hills riders can not create enough hand rim friction force in 1:1 on standard wheels to control the wheelchair.
- Minimal additional weight
  The capability for going up-hill with lower gears can not offset a major increase in additional weight. Target is <10lbs additional weight.
- Fits on most common wheelchairs
  There are a wide variety of wheels chairs manufactured and there are no standards for how the wheels are connected to them. Thus the resulting product must be universal or have fittings to enable it to fit most chairs.
- Payment approved by insurance, Medicare/Medicaid and VA
  Virtually all mobility aids are paid for by insurance companies, Medicare/Medicaid or the Veterans Administration. Thus, it is imperative that the resulting product be something they approve and will pay for. Typically Medicare pays approx. 80% of the purchase cost and the occupant is responsible for the remaining 20% or this may be covered by secondary insurance.

This is a difficult set of requirements and it took **MAGIC**WHEELS over 10 years to resolve them and bring a product to market. Videos, referenced at the end of this Case Study, show how well **MAGIC**WHEELS met them. The rest of this case study focuses solely on those requirements that Steve and his colleagues struggled with.

Meeting the Requirements

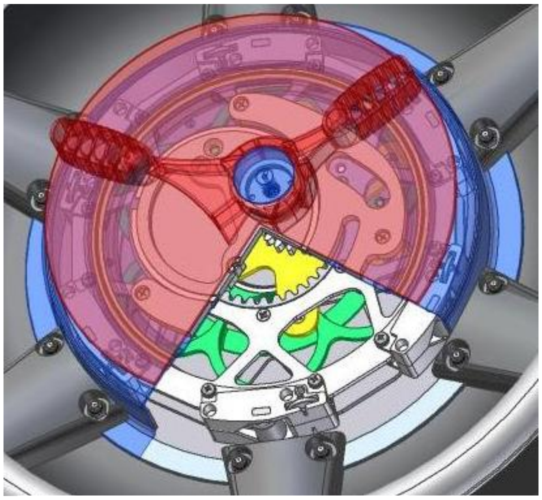


Figure 3: A cutaway of the Magic Wheel transmission

There have been many attempts to meet the customers' requirements over the years. A patent search has turned up over 20 different designs. These concepts range from complex lever systems, to planetary gear sets much as those used in 3-speed bicycle hubs and in the Ford Model-T transmission (a two speed transmission much as needed here). Steve and his colleagues at **MAGIC-**WHEELS studied these patents and realized that none of them could meet the requirements. For most, the interface between the user and wheelchair was complex. For others, the inability to control roll-back, lack of hill-holding and windage were critical.

What became **MAGIC**WHEELS began with research efforts at the University of Washington in 1993-94. The company, **MAGIC**WHEELS, was founded in 1996 to refine these 2-speed ideas and bring them to market. Government grants to fund the development effort were applied for and initially rejected. Finally after two years grants through the NIH and other government agencies were secured. To date, about $2M in development money has been expended.

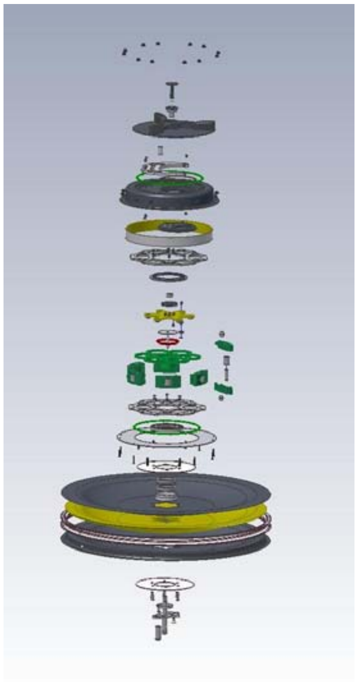


Figure 4: An exploded view of the MAGIC-Wheels transmission

The key to **MAGIC**WHEELS is the use of a hypocycloidal gear train with a ring gear, a spur gear and a hold gear (Figure 3). The ring gear is directly affixed to the wheel. The spur and hold gears move in and out of engagement in a plane with the ring gear depending on the position of the shifter (Figure 5). The spur gear is engaged for the low-gear configuration (push the shift handle forward, clockwise in Figure 4) and orbits the inside of the ring gear but does not rotate on its own axis; it is fixed to the non-rotating orbiting plate behind it. The hold gear is engaged for the 1:1 configuration (pull the shift handle back) but just locks the wheel and gears into a solid rotation. The mechanizm for this is quite complex and beyond this article. It can be seen in the cutaway in Figure 3, but is best appreciated by viewing the on-line videos referenced at the end of the article.

The resulting system is complex with over 300 parts (Figure 4). Before concluding that this is overly complex for the function it serves note that before **MAGIC**WHEELS, No system could achieve the above requirements. Further, before **MAGIC**WHEELS Medicare had only two code categories for Wheelchairs, Manual and Powered. There was no category to cover multiple speed manual wheelchairs. It took **MAGIC**WHEELS over two years of working with Medicare to get a code established for this classification (created in Jan 2008).

Figure 5: The shifting action needed

During the development of this system, once committed to the hypocycloid, progress got stuck in that it did not shift well enough to bring to market. It was necessary to move the hand rim while moving the shifting lever back & forth to get the gears to mesh. This motion required two hands violating an important design requirement. They worked on this problem for six months. As a funding deadline approached they knew they had to resolve the issues. They tried many things, each helped a little. For example, they changed the shape of the gear teeth to allow them to not only engage and disengage more easily, but to make shifting so that the new gearing is made before the old one is release to maximize safety. As time was running out, Steve noticed that the hand rim only needed to move in one direction to initiate shifting - in the opposite direction of the natural motion shown in Figure 5. It was 2:00AM one morning that he realized that reversing the system would alleviate most of the problems.

So they reversed the parts (left to right) and put the transmission together backwards. With this the hand rim and shift handle move in the same direction during shifting and the friction on the gear box from moving the shift handles also moves the hand rim slightly in the same direction providing smooth single handed shifting. This reversing of the parts resolved the problem and afforded one hand powering and shifting on each wheel. This allows a wheelchair user to approach a hill in high gear, coast up a little and then hold the shift levers as the wheelchair stops and coasts backward slightly thus shifting into the low gear which stops the backward motion as it is automatically in hill-holding mode. The entire shifting motion was now close to the ideal painted by the requirements.

A young colleague asked Steve how he thought of reversing the parts and he told him that you must try everything. He knew there had to be a solution and if you look long enough you will find one. He spent many months of mental and physical trial and error to solve the problem.

Steve has over 40 years of design experience. He has learned many tricks for un-sticking his thinking. Common methods for un-sticking problems are recapped and related to Steve’s experience in the next section.

Un-sticking the Thinking

Typically, when facing a dilemma during design the situation is something like:" If I improve X, I will adversely affect Y, How can I improve them both?" This is often referred to as a "trade-off" "conflict" or "contradiction". Two methods for articulating and studying contradictions are: a) using patching guidelines, and b) TRIZ. Each of these can help un-stick design problems caused by contradictions.

"Patching" is a term widely used in software development for fixing contradictions. There are eight patching guidelines that work well with mechanical devices (see Section 9.3.5 in *The Mechanical Design Process*). They are:

1. *Combining:* Make one component serve multiple functions or replace multiple components. Combining will be strongly encouraged when the product is evaluated for its ease of assembly (Section 12.5).
2. *Decomposing*: Break a component into multiple components or assemblies. As new components or assemblies are developed through decomposition, it is always worthwhile to review constraints, configurations, and connections for each one. Because the identification of a new component or assembly establishes a new need, it is even worthwhile to consider returning to the beginning of the design process with it and considering new requirements and functions.
3. *Magnifying/Minifying*: Make a component or some feature of it bigger/smaller relative to adjacent items. Exaggerating the size or number of a feature will often increase one's understanding of it. Make one dimension very short or very long. Think about what will happen if it goes to zero or infinity. Try this with multiple dimensions. Sometimes eliminating, streamlining, or condensing a feature will improve the design.
4. *Rearranging*: Reconfigure the components or their features. This often leads to new ideas, because the reconfigured shapes force rethinking of how the component fulfills the functions. It may be helpful to rearrange the order of the functions in the functional flow. Take the current order of things and switch them around. Put what is on top, on the bottom; or what is first, last.
5. *Reversing*: Transposing or changing the view of the component or feature; it is a subset of rearranging. Try taking what is the inside of something and making it the outside or vice versa. Or try switching left for right.
6. *Substituting*: Identify other concepts, components, or features that will work in place of the current idea. Care must be taken because new ideas sometimes carry with them new functions. Sometimes the best approach here is to revert to conceptual design techniques in order to aid in the development of new ideas.
7. *Stiffening*: Make something that is rigid, flexible or something that is flexible, rigid.
8. *Reshaping*: Make something that is first thought of as straight, curved. Think of it as cooked spaghetti that can be in any form it wants to be and then hardened in that position. Do this with planar objects or surfaces.

Relating these to Steve's situation at **MAGIC**WHEELS, what solved his problem was #5 - Reversing. However, before that he had reshaped the gear teeth (#8). In fact these types of patches are so common, that a Russian patent inspector realized that they were the essence of most good ideas. After he reviewed many thousands of patents, he developed a very complete list of, what he called, the 40 Inventive Principles. He found that these 40 inventive principles underlie all patents. These are proposed "solution pathways" or methods of dealing with or eliminating engineering contradictions between parameters.

The Inventive Principles are part of TRIZ (pronounced "trees") the acronym for the Russian phrase "The Theory of Inventive Machines." This method developed by Genrikh (or Henry) Altshuller, a, mechanical engineer, inventor and Soviet Navy patent investigator. After WWII Altshuller was tasked by the Russian government to study world-wide patents to look for strategic technologies the Soviet Union should know about. He noticed that some of the same principles were used over-and-over again by totally different industries, often separated by many years, to solve similar problems.

From his findings Altshuller began to develop an extensive "knowledge-base" which includes numerous physical, chemical, and geometric effects along with many engineering principles, phenomena and patterns of evolution. Altshuller wrote a letter to Stalin describing his new approach to improve the Rail System along with products the USSR produces. The communist system at the time didn't value creative/free thinking. His ideas were scorned as insulting, individualistic and elitist, and as a result of this letter, he was imprisoned in 1948 for these capitalist and "insulting" ideas. He was not released until 1954, after Stalin's death. After the 1950s, he published numerous books, technical articles, and taught TRIZ to thousands of students in the former Soviet Union.

Altshuller's initial research in the late 1940's was conducted on 400,000 patents. Today the patent data-base has been extended to include over 2.5 million patents. This data has led to many TRIZ methods. Only part of the most basic one will be described here. This method makes use of Contradictions and Inventive Principals. The links at the end of the paper give a complete list and description of the principles, a super-set of the eight patching guidelines.

The first step in using TRIZ is to discover the contradiction. In Steve's case it was evident, when the gears are shifted; the motion is in the wrong direction. In many cases the contradiction is not so evident and so there are methods within TRIZ to discover them (A method to find contradictions is presented in Section 7.6 in *The Mechanical Design Process*)

The second step is to use contradictions as an index to the 40 principles to discover which may apply. This indexing method is not covered here. Rather a couple of the Inventive Principles found through using it will be discussed. These inventive principles are:

Principle 2. Inversion

- **a.** Instead of an action dictated by the specifications of the problem, implement an opposite action
- **b.** Make a moving part of the object or the outside environment immovable and the non-moving part moveable
- **c.** Turn the object upside down

  Example:

  1. Abrasively clean parts by vibrating the parts instead of the abrasive

This is very much like patching guideline 5, Reversing. As said earlier, the guidelines are a subset of the TRIZ Principles. Clearly this principle can help focus thinking in the direction that ultimately solved Steve's **MAGIC**WHEELS problem.

Other potential solutions suggested by the indexing the Inventive Principles are:

Principle 3. Mechanical vibration

- **a.** Set an object into oscillation
- **b.** If oscillation exists, increase its frequency, even as far as ultrasonic
- **c.** Use the frequency of resonance
- **d.** Instead of mechanical vibrations, use piezovibrators
- **e.** Use ultrasonic vibrations in conjunction with an electromagnetic field

  Examples:

  1. To remove a cast from the body without skin injury, a conventional hand saw was replaced with a vibrating knife
  2. Vibrate a casting mold while it is being filled to improve flow and structural properties

Principle 14. Spheroidality

- **a.** Replace linear parts or flat surfaces with curved ones, cubical shapes with spherical shapes
- **b.** Use rollers, balls, spirals
- **c.** Replace a linear motion with rotating movement, utilize a centrifugal force

  Example:

  1. Computer mouse utilizes ball construction to transfer linear two axis motion into vector motion

Clearly each of these Principles suggests other solutions. Principle 3 suggests jiggling the hand rim, the action that helped Steve discover his ultimate solution. And, Principle 14 suggests changing the shapes of surfaces and interfaces – Steve changed from a linear shifter to a rotary one in going from the first generation prototype to the 2nd and he changed the gear tooth shapes to improve shifting. There may be many other ideas in the 40 Principles.

Conclusion

Although Steve did not formally use the eight patching methods or TRIZ, his years of experience have instilled many of these guidelines and Principles in his thinking. As he struggled to un-stick the problem, he combined, reversed, and changed the shapes of things until he finally hit on the solution. Formalizing contradictions and using the guidelines and principles can shorten the time to a solution and the quality of it. The final **MAGIC**WHEELS product is creating a new market and is receiving strong endorsement from wheelchair users who are escaping from flat-jail.

Resources

Videos showing **MAGIC**WHEELS structure and use:

- A series of videos on UTube show how Magic Wheels works: http://www.youtube.com/watch?v=fpqmmWjxuEE

- A series of videos on the **MAGIC**HEELS web site show them in use and how they meet the customers' requirements. http://www.magicwheels.com/gallery/index.htm

TRIZ 40 Inventive principles are at

- List of inventive Principles
- www.triz-journal.com. The TRIZ Journal is a good source for all things TRIZ.

Author

This case study was written by David G. Ullman, Emeritus Professor of Mechanical Design from Oregon State University and author of *The Mechanical Engineering Process*, 4th edition, McGraw Hill. He has been a designer of transportation and medical systems and hold five patents. More details on David can be found at www.davidullman.com. David was assisted by Steve Meginniss, founder and CTO of **MAGIC**WHEELS, Inc. in Seattle, Washington.

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