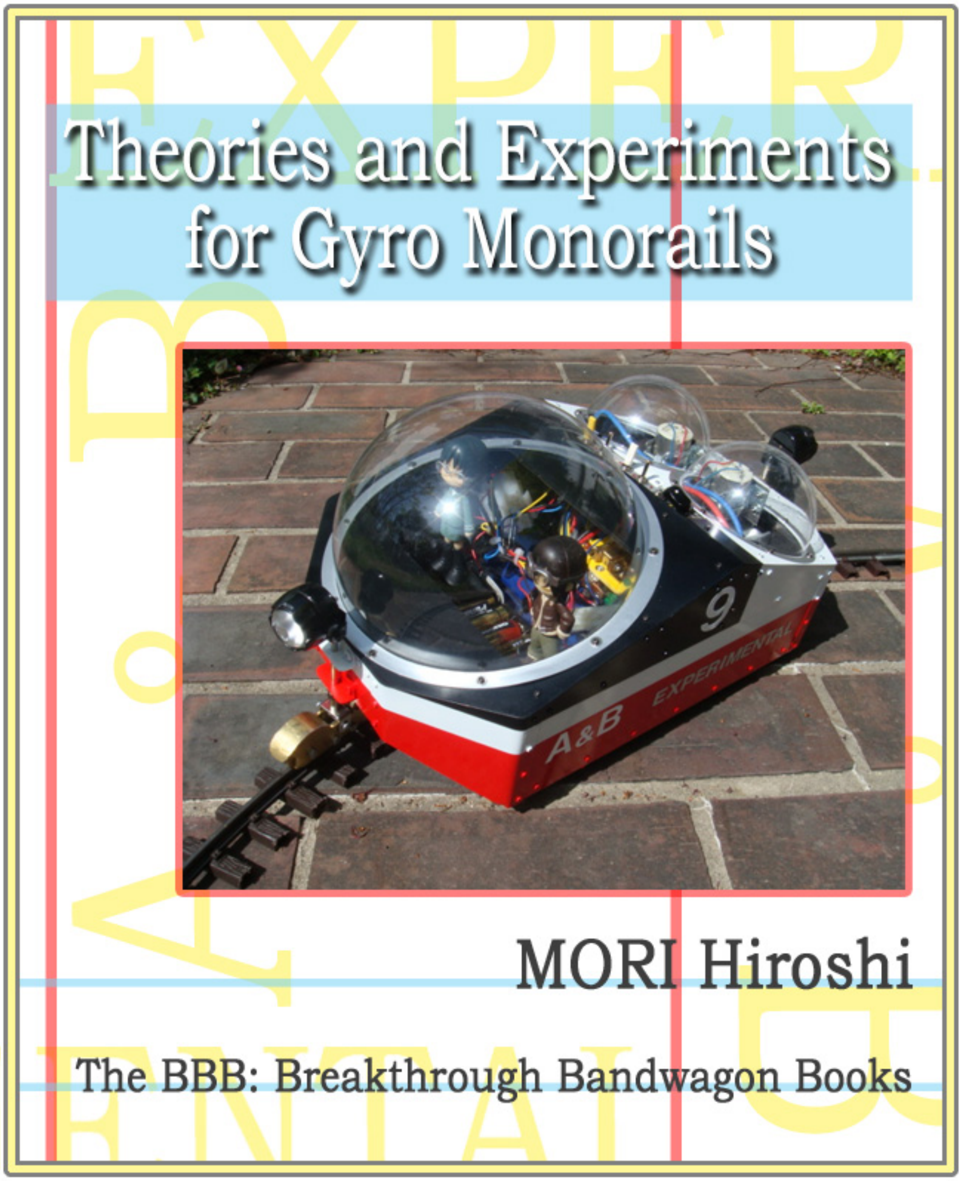
Theories and Experiments for Gyro Monorails



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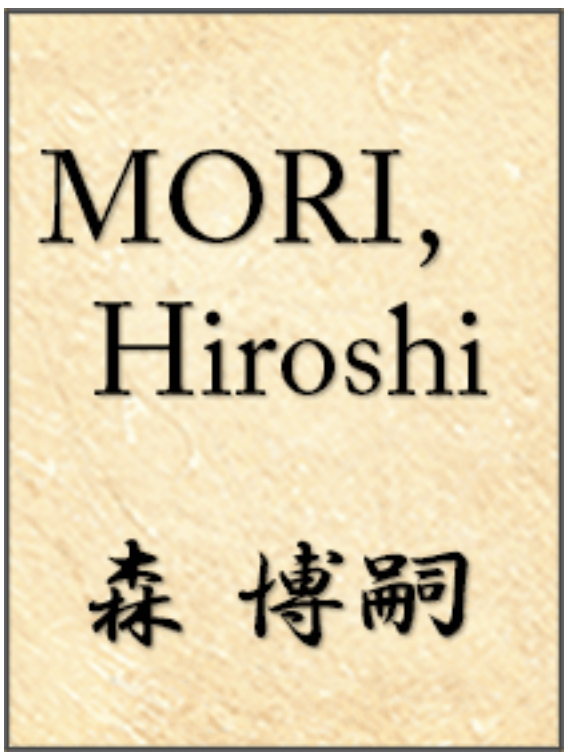

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0. About This Article

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1. How It Started

It was at the JAM Convention (International Railway Model Convention) held in the summer of 2007. Among the locomotive models made by Mr. Akio Inoue, the most outstanding one was a red gyro monorail (Photograph 1). Unfortunately, the model was incomplete. In fact, I heard directly from Mr. Inoue himself that he had been trying to build this unprecedented model. Rather, he even sought advice from me. I was a little nervous to say the least, because it was rare for the one whom I look up as my mentor to do so. Probably, he decided to ask me because I was teaching dynamics at a university.

【Photograph 1】A gyro monorail made by Mr. Akio Inoue (Photographed by Mr. Akio Inoue in 2007)

My major was not exactly the same as dynamics. Rather, my specialty is numerical analysis of viscous fluids. In this field, it is more about programming rather than setting up theoretical formulas. However, general education curriculums were dismantled during the university reformations, so I was forced to be in charge of a mathematical class for undergraduates. I had to visit other departments to give lectures of cross and dot products of vectors, and calculus. Because I was unaccustomed to them, I had to study them very hard. Even though I hardly studied them back in the days of entrance examinations, I was given no choice but to study them for my job at that point. After my lectures, I was often asked by students, “How would this be useful for our lives?” It was what I myself wanted to ask. I think about how it has actually become useful for me ... In this occasion, in order to successfully build a gyro monorail, I needed that very mathematics.

When I was an elementary school student, I was interested in mobile toys, and eventually started building model trains. It was designed only to move forward with a motor. At a glance, it was structurally simple, compared to other types of models. Surprisingly, even simple maneuvers such as running and turning at a curve were profoundly deeper than expected. I am so clumsy as a handicraft enthusiast, to the extent that I have finally gotten the skills to build a gear box that is barely useful only recently. However, gyro monorail, compared to other types of railroad train models, is extremely unique and mechanically interesting. Even though a gyro monorail is easier than a radio-controlled helicopter in general, the adjustments involved in them are equally difficult with each other.

Anyway, after attempting to make several trial products, I started feeling that I have finally overcome the first hurdle. So, I had decided to contribute for the first time an article to "Hobby of Model Railroading", the magazine I admire.

Model No. 7 in G scale (newer than Model No. 9)

2. Historical Background

A gyro monorail is a railroad train running on a single rail (Gyrocars running on conventional plain roads once existed.) It carries a gyroscope with a rotating wheel, and keeps its balance with the precession of the gyroscope. Even when it stops, it stands without falling down. What decisively differs from other types of monorails is that it can run on existing conventional railway tracks. It needs only one rail, so its scale does not matter.

Originally, the gyro monorail was invented and developed in the United Kingdom by Louis Brennan. At about the same time, August Scherl made it in Germany. For both cases, full-sized prototypes were made in the beginning of the 20th century, and were displayed in exhibitions and such.

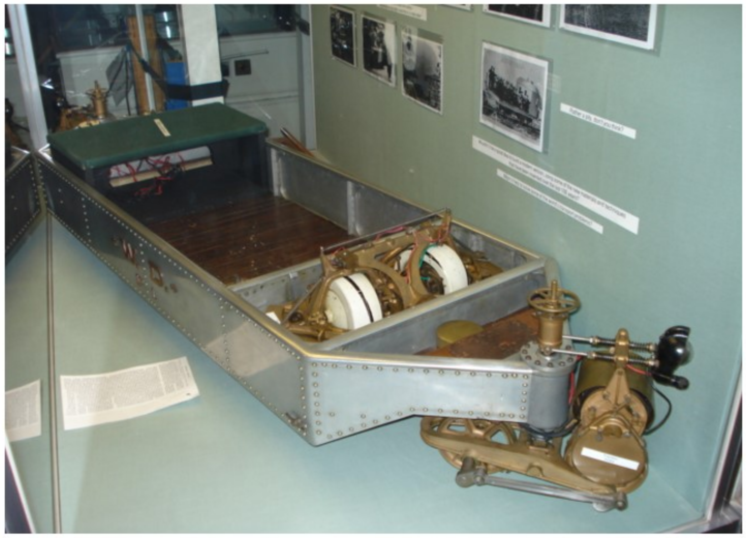
I can point out several advantages of the monorail. The most appealing point among them is that it can make a sharp turn at a curve at high speed. It makes a turn while leaning like an airplane does, so that the passengers do not have to experience the dynamic effect of the centrifugal force by sliding toward the outer curve. Since it can deal with far sharper curves without losing the speed, it is convenient for planning to lay railway tracks.

As for its safety, unlike conventional train cars running on two rails, it is not going to tip to one side suddenly due to the excessive exterior force applied from the other side. (Conversely, it tries to swing back to the direction from which it receives the force.) Also, even when it derails, it does not get toppled over sideways. That is the reason why the developers insisted it was safer than other types of railroad cars.

The invention of gyro monorail was reported in Japan back then. It was even considered to be the invention that would change the history of railroad transportation. However, it was considered to be energetically and mechanically wasteful, for not only the locomotive cars but also the freight cars and passenger cars needed to be mounted with gyroscopes. It was noted as the shortcoming.

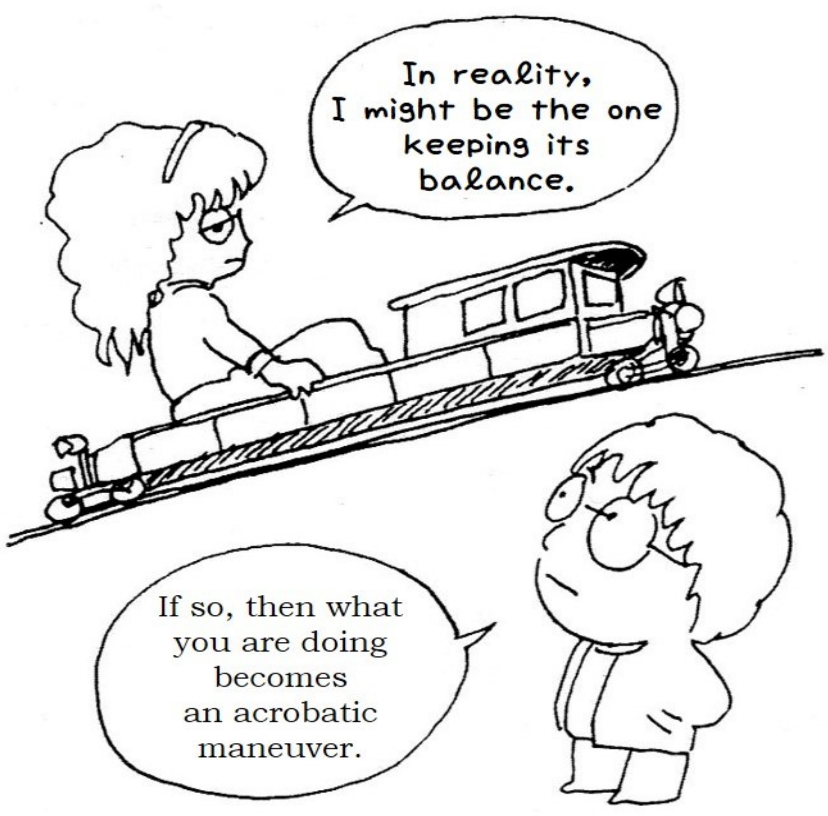
It is said that gyro monorail was actually planned and had even advanced to the actual production phase in India and Russia. However, in the end, it did not turn out to be realized. Only the demonstration car, which could accommodate more than twenty people at a time, made by Brennan for exhibitions, had been in operation in an amusement park for about two decades, but it disappeared in 1930.

After Brennan, Pyotr Shilovsky, a Russian, continued to conduct the research. However, his main theme was not for railroad cars, but for gyrocars. Additionally, the researches were conducted in the United States for a certain period in 1960s. It did not quite make too much progress from the level of Brennan's prototypes.



【Photograph 2】 Small-sized gyro monorail car made by Brennan
(at National Railway Museum in York, England. Photo by Mr. Kimio Hoshino.)

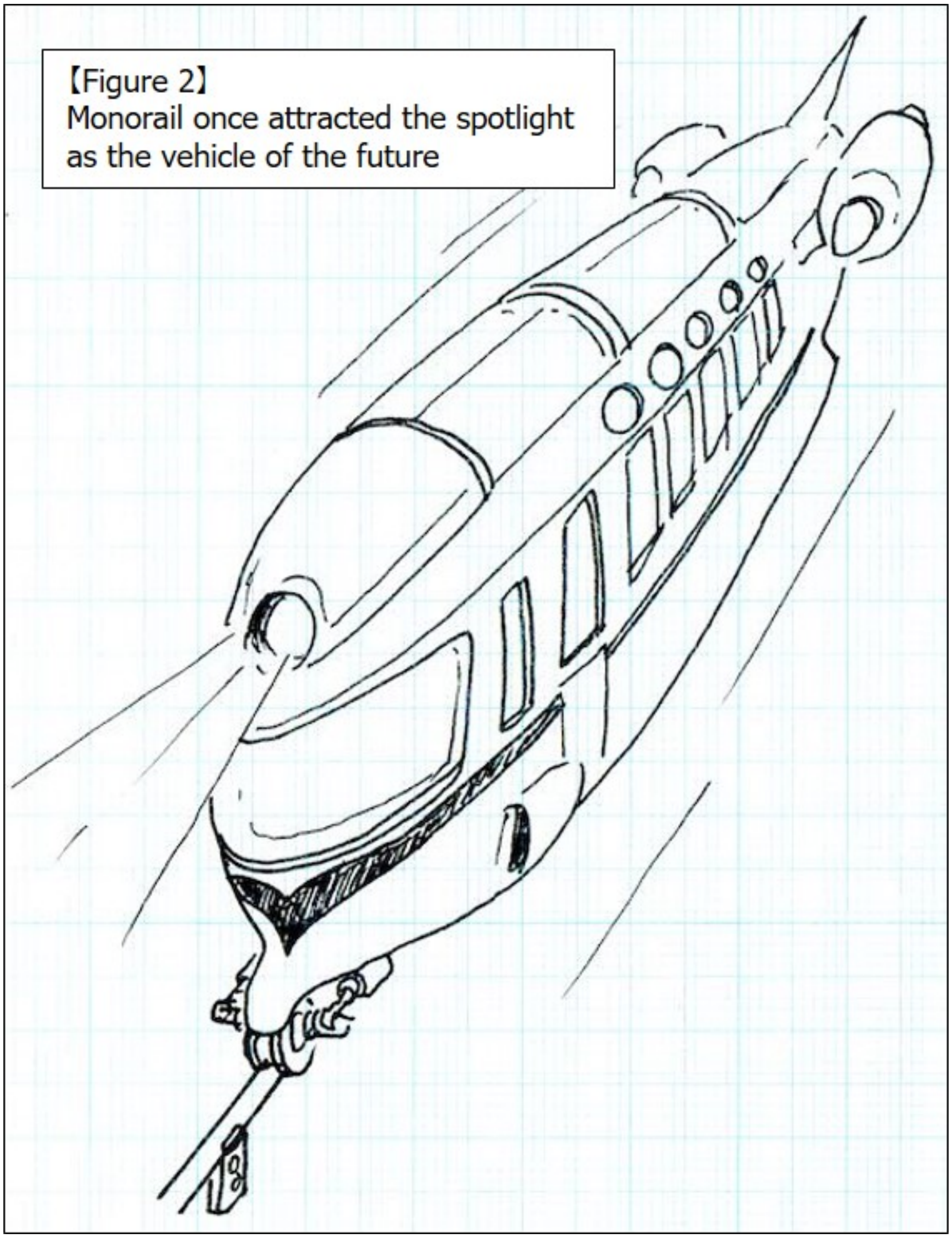
In the early phase of his study, Brennan made models of gyro monorail (Photograph 2). He laid rails on his garden (said to have used gas pipes as rails) and had the models run on them. The length of the car model was 1.8 meters. The width was 46 centimeters. It is said that it ran through sharp curves, steep slopes, and even a bridge made of one wire rope. A photograph in which he had his daughter ride on it for demonstration still remains (Figure 1).



【Figure 1】 Brennan's demonstration

Since the monorail looked mysterious at a glance, it seemed to become the center of attention. It probably generated a huge impact. Many models and toys of gyro monorails were made. Also, many illustrations of gyro monorails as futuristic vehicles were featured in science magazines and such.

The reason why monorails attracted attention back then was the demand for higher speed. I suppose it had the ideal figure when people imagined the high-speed train transportation of the future (Figure 2).



【Figure 2】
Monorail once attracted the spotlight
as the vehicle of the future

3. Principles and Mechanisms

Simply put, I can say, "It maintains its balance with the gyroscope." The statement like, "Spinning tops don't easily fall down. So, a top that is rotating inside the vehicle allows the effect of maintaining the balance to keep the vehicle upright.", is half-correct. But, it is just an explanation with words, not scientific knowledge or comprehension. Moreover, just having a rotating wheel does not make a gyro monorail.

By the way, two-wheeled vehicles such as bicycles and motorcycles can run without gyroscopes by maintaining the balance sideways. It is because such vehicles can freely change their courses while running. If the wheels are on a rail and their sideway movements are limited, the two-wheeled vehicles cannot run properly anymore. Running on a rail is technically more difficult, and we need gyroscopes in the end.

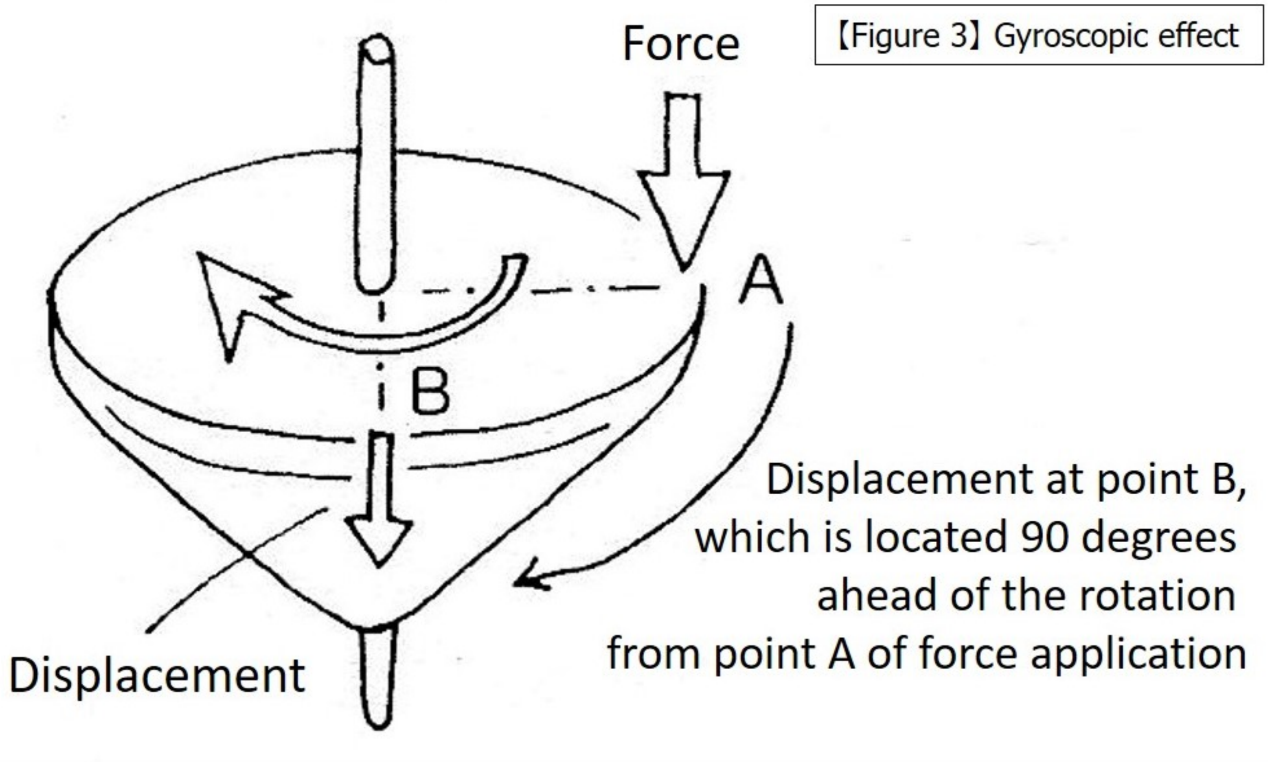
To begin with, why don't spinning tops fall down? Why can we say, "Rotating objects don't fall down?"

Spinning tops do not fall down because of the "gyroscopic effect", which I will discuss later. In other words, it is due to "the tendency to be displaced to a direction that is different from the direction to which the force is applied." Also, friction works at the point where the axis of a top makes a contact with the ground. Counter torque of the rotation affects the top, and it puts the slant of the axis back to the upright position. If you make the tip of the axis sharper and decrease the friction of the contact point, the top will not be able to maintain the standing position too well.

3.1 Gyroscopic Effect

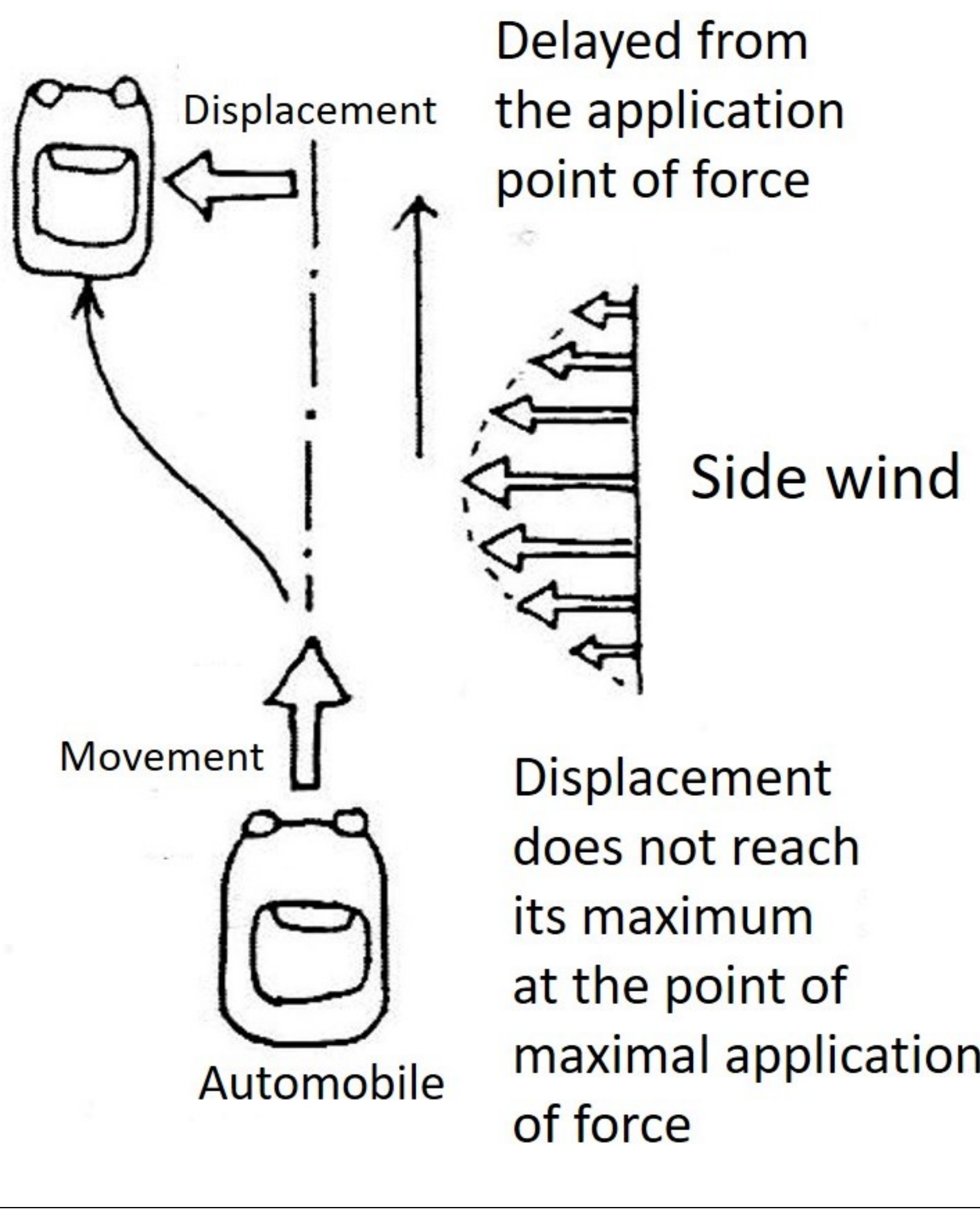
When a rotating object receives a force that tries to tip the axis, the axis will be tilted to the direction that is shifted by 90 degrees to the direction of the rotation from the force vector (Figure 3). If you have a Chikyu Goma, you can get the feel of how this works. You will be led into thinking that you are experiencing the mystic force of some sort.

【Figure 3】Gyroscopic effect

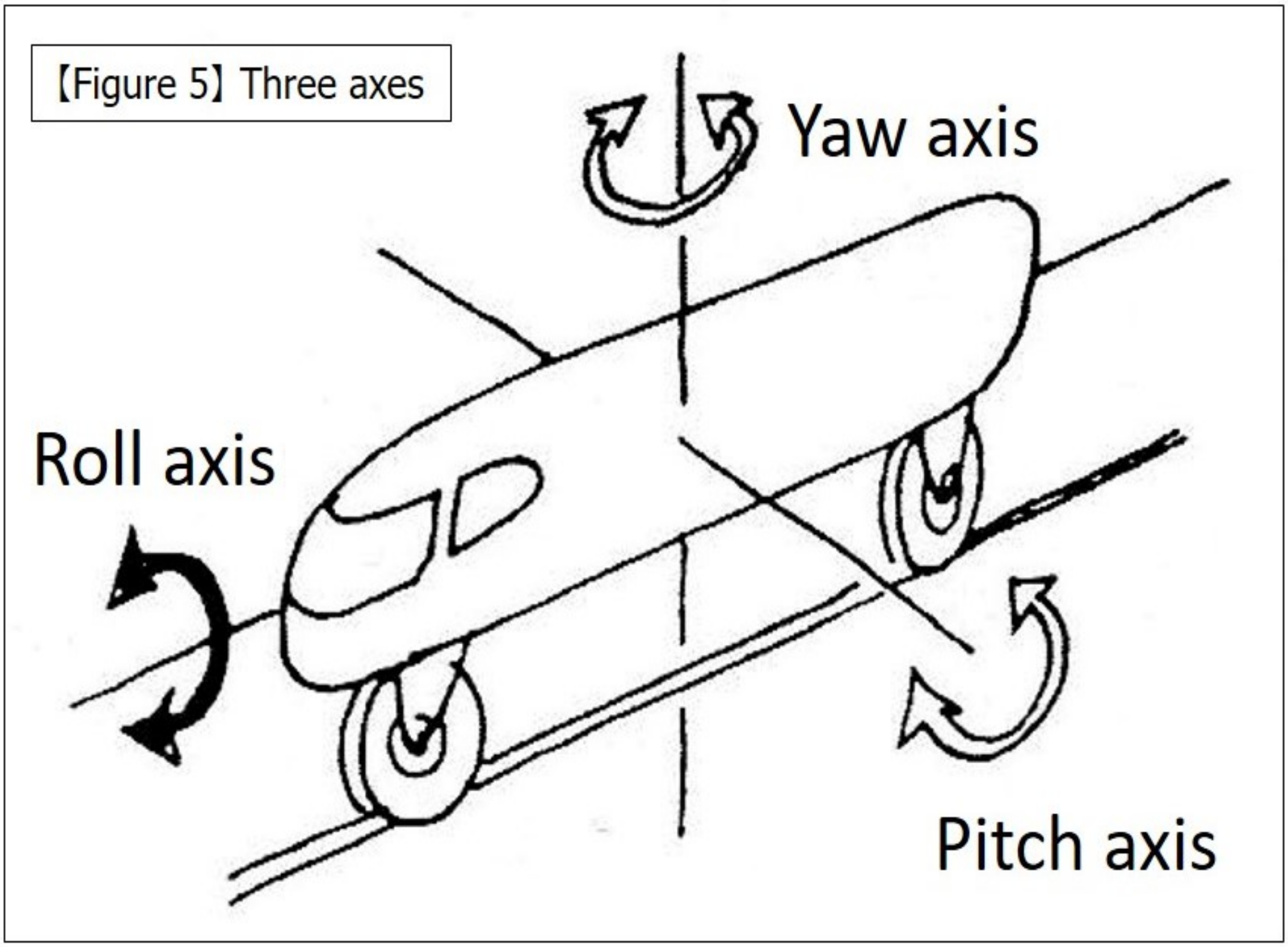


It is difficult for me to explain the gyroscopic effect without using a mathematical formula (vector or cross product). I would like you to assume a situation in which an automobile is being pushed to the leeway by the side wind. When a running car receives side wind, it will skid sideways most at the point that is slightly ahead in the direction (Figure 4). It is based on the principle, in which the integration of a trigonometric sine curve leads to the curve, the phase of which is shifted by 90 degrees. A rotating object experiences what is equivalent to continuously and repeatedly passing by the point at which it receives the side wind. The more frequently it passes by the point, the bigger the effect is. Therefore, the faster it rotates, the bigger the torque, the phase of which is shifted 90 by degrees, will be.

【Figure 4】Automobile receiving side wind



When a monorail is loaded with a gyroscope and the car tilts with respect to the roll axis, the gyroscope tends to lean toward the direction that is different by 90 degrees. Conversely, if you try to tip the gyroscope, the car tries to lean toward the direction that is diverted 90 degrees from it. Just like this, a gyroscope that is mounted on the car can convert the roll axis rotation into the pitch axis rotation or the yaw axis rotation. As for monorails, only the roll axis is unstable, and the other two axes can secure the reactive force with the rail and the wheels (Figure 5). Based on this logic, the stability with respect to the roll axis is maintained.



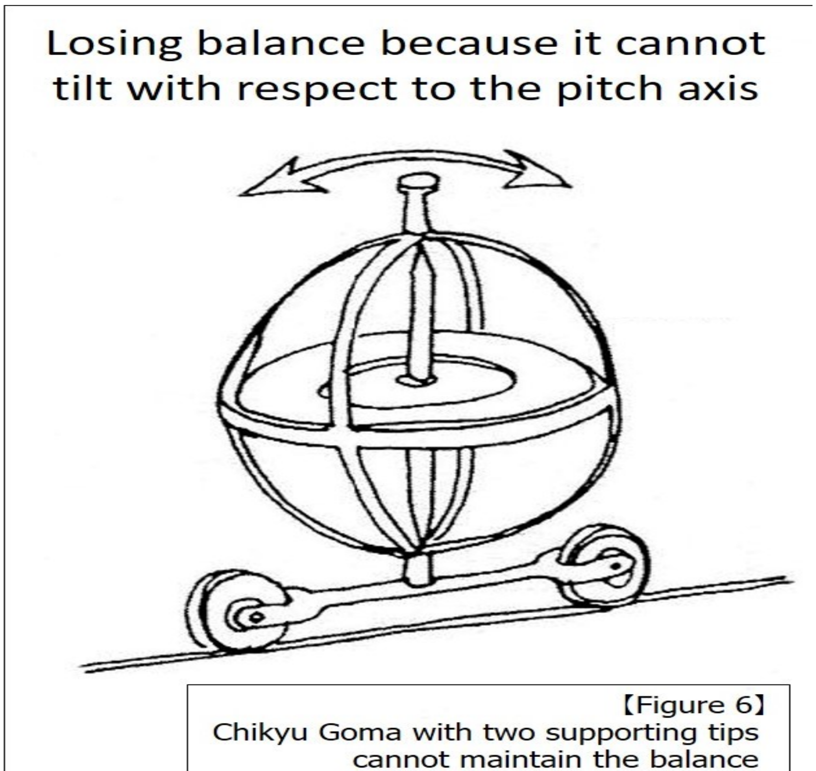
3.2 Precession

When a top leans to a certain direction, it tries to fall down toward the direction that is shifted by 90 degrees. However, tilting to the direction moves the center of gravity and the gravity attempts to pull down the spinning top. Then, the gyroscopic effect, which is being displaced to the direction that is shifted by 90 degrees, takes place. As a result of that, the spinning top precesses repeatedly. It is what is known as the "precession". As a gyroscopic motion, there is also the motion of nutation that involves high frequency components, along with this precession. Even though it is quite a complicated problem, it is not to be discussed it in this article. Roughly speaking, I would like to assume optimistically that the nutation involved in the miniaturized models tends to get minimized due to the elements such as frictions of the devices.

Unlike usual tops, a Chikyu Goma has a frame that does not rotate. The tip of the leg of the frame has a thin groove. A player can enjoy making the Chikyu Goma perform a tightrope act by placing it on a thread and such. The toy named Gyroscopic Jockey, which runs at high speed around the ring-shaped course instead of a thread, was in the market (Photograph 3).

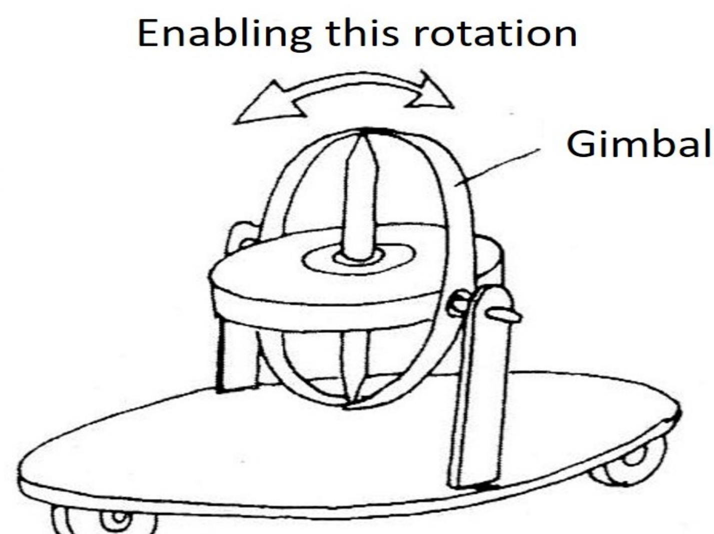
【Photograph 3】Chikyu Goma and Gyroscopic Jockey
(made by Tiger & Co., Ltd.)

Unfortunately, one cannot get a gyro monorail just by mounting a Chikyu Goma on a car. First, a Chikyu Goma fails to stand upright just by having two contact points to stand on. Although many might end up naturally thinking that having two contact points for the support makes the top more stable than that with just a single leg, that is not the case (Figure 6). The reason is that the top can no longer tip to the direction due to the extra leg and the precession motion cannot continue. The Gyroscopic Jockey has one wheel. A classic German toy, which is a spring-driven gyro monorail model, is also a monocycle.



【Figure 6】
Chikyu Goma with two supporting tips
cannot maintain the balance

Therefore, if a gyroscope is mounted on a monorail car, which cannot tip (rotate) with respect to the pitch axis, then the gyroscope has to be installed in a frame named gimbal, and the gimbal has to be able to lean to a certain direction freely (Figure 7).



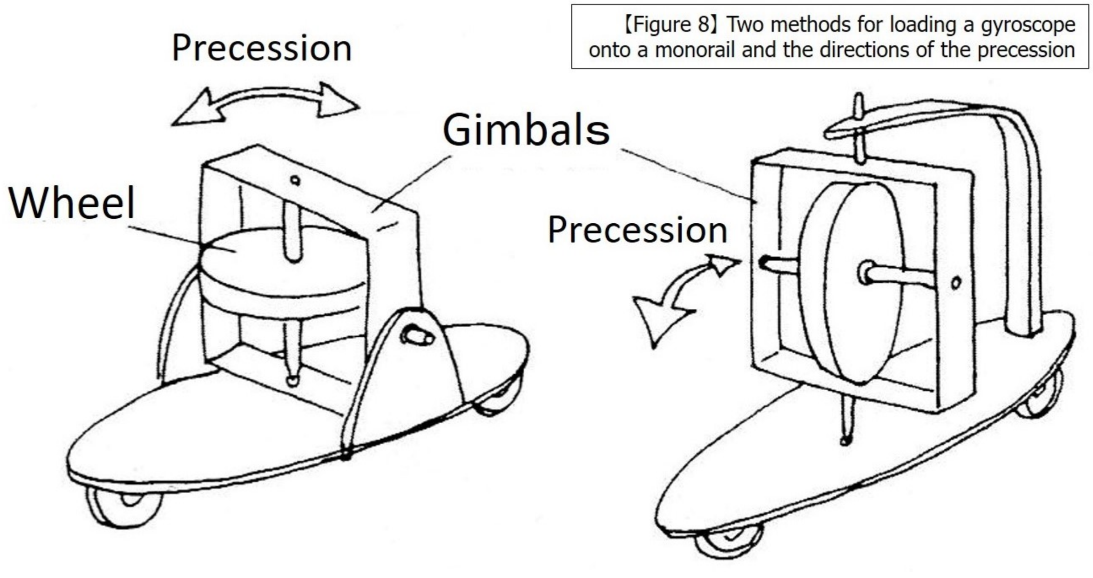
【Figure 7】Gimbal that enables precession

3.3 Gyroscopes Needed for Monorails

A Chikyu Goma is not power-driven, and the rotational force that is given initially decays gradually due to the friction. Gyroscope is the mechanism that maintains the high rotational speed by having the attachment of the power drive.

There are two ways to mount a gyroscope onto a monorail. The rotational axis of the gyroscope has to be directed to any of the axes other than the roll axis of the car. The remaining axes are the vertical axis, and the horizontal-lateral axis (Figure 8). Then, the precession of the gimbal is allowed to the remaining direction (in each way of mounting the gyroscope) by being provided with the new degree of freedom of movement. In other words, for the gyroscope with the vertical axis, the gimbal allows the precession with respect to the pitch axis. For the gyroscope with the horizontal-lateral axis, the precession is allowed with respect to the yaw axis.

【Figure 8】Two methods for loading a gyroscope onto a monorail and the directions of the precession



If the monorail only needs to go straight, either of the gyroscopic configurations mentioned above would be sufficient. However, since it is a vehicle, its routes are destined to have curves and slopes.

The gyroscope secures the stability of the roll axis. However, the gyroscope reacts to the leaning (rotation) of the other axis that is oriented vertical to the axis of rotation. In short, the problem is that the vertical gyroscope and the horizontal gyroscope interpret the rotations with respect to the pitch axis and the yaw axis, respectively, as the “tilt” of the car.

The idea that Brennan came up with to solve this problem was to use two gyroscopes, which were rotating to the directions opposite to each other. It was the mechanism in which both of the two gyroscopes cancel each other’s unnecessary precessions. It has been said that the invention allowed gyroscopes to be used for practical uses as stabilizers. (It would be used not only for monorails but also for ships and torpedoes.)

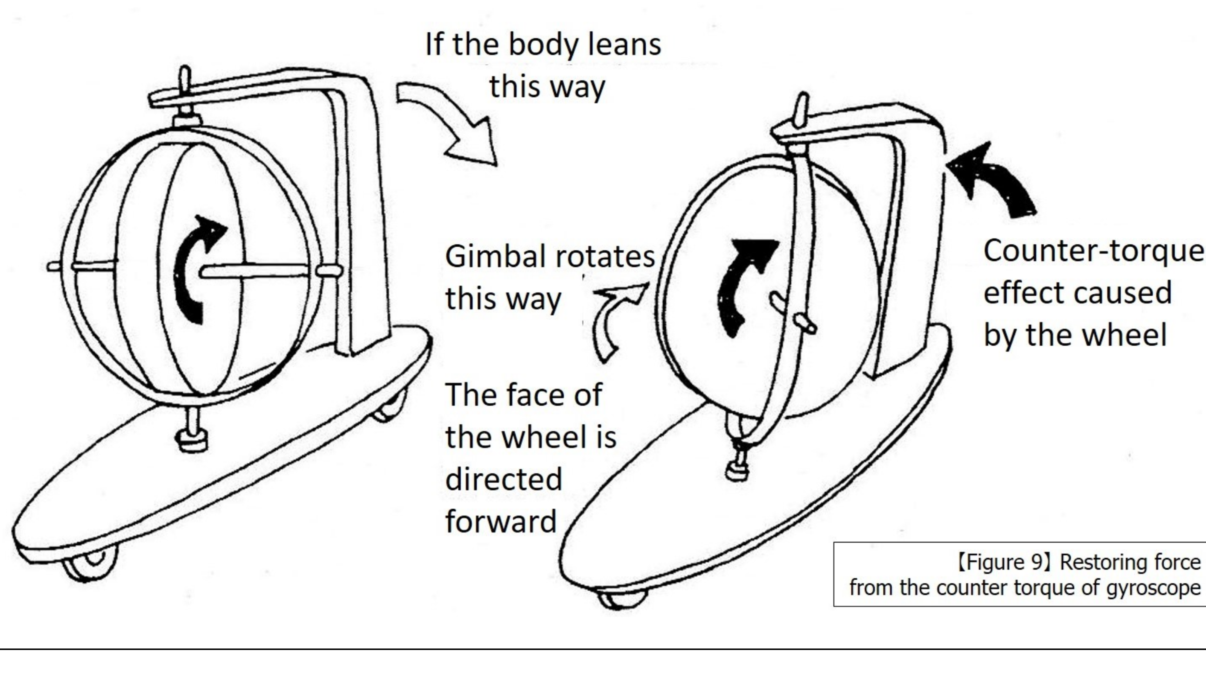
When it comes to a full-sized vehicle, the energy that is used for driving the gyroscope becomes an issue. For the case of an actual vehicle that was made one hundred years ago, the high efficiency was achieved by putting the wheel of gyroscope in a vacuum container to eliminate the friction as much as possible. Once it gains a certain rotational speed, the energy to maintain the rotation depends on the friction. It is said that the wheel rotating in the vacuum kept on rotating for more than 30 minutes after the power was turned off. If it faced a mechanical accident, there would be a plenty of time for stopping the car, evacuation, and preparing the physical support to keep it standing.

Incidentally, the model made by Mr. Inoue was equipped with retractable gears, which were modified parts of a radio-controlled aircraft. It was a really amusing idea. The author is thinking about making a little larger gyro monorail, and loading such gimmicks on it.

3.4 Balancing System

3.4.1 Free Gyroscope

Only by loading a gyroscope that freely precesses, it can attain the stability within the limited range. It is because the counter torque of the rotating wheel reacts to put the tilt of the car back to the upright orientation when the gyroscope gimbal leans and its rotational axis gets closer to being aligned with the roll axis of the car (Figure 9). When the car is relatively light compared to the gyroscope, it can stand on its own. In order to enhance this effect, the air resistance of the wheel has to be increased to boost the counter torque.



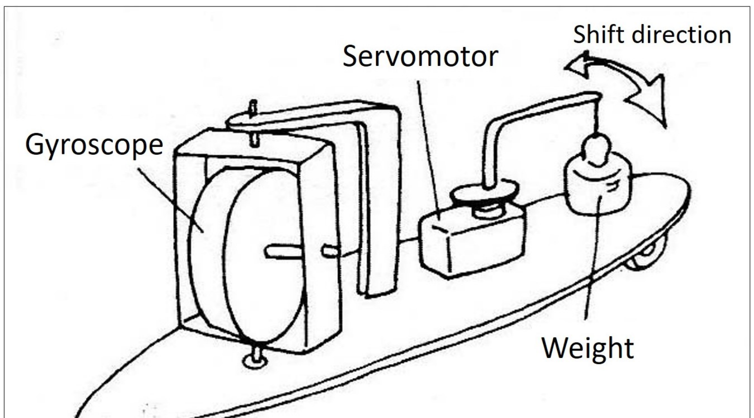
【Figure 9】Restoring force from the counter torque of gyroscope

However, the restoring force attained from this counter torque is relatively small. If you try to rotate the gyroscope with a motor, then the weight will be heavier with batteries and such, and the mechanism to run the monorail will be needed. Additionally, as mentioned earlier, it is impossible to make a turn at a curve with a single free gyroscope. Twin gyroscopes will be necessary, and the linkage between the two gyroscopes will have to be added. The free gyroscope is too weak to support the total weight of these. Moreover, turning at the curve will be affected by the centrifugal force. Even if the car may happen to have twin gyroscopes, it cannot withstand the loss of stability only with the counter torque of the rotation.

Therefore, the mechanism to actively maintain its balance is needed. It is called the balancing system in this article. There are several methods to the system.

3.4.2 Weight Shifting Method

The simplest method that anyone can come up with is the one that has the weight that shifts to the right and left laterally (Figure 10). It appears that this method was once used for an actual vehicle. The author also experimented by using models several times. It was difficult to control the model delicately. If the servomotor attempts to move the weight, the acceleration to the opposite direction occurs in the initial phase of the motion. It is not that it generates no useful effect. It is possible to maintain the upright orientation of a small model by controlling the servomotor manually. But the skillful operation is essential, like the case for letting a radio-controlled helicopter hover. In order to automate the mechanism to maintain the balance, electronic controls with microcomputers are likely to be absolutely necessary. The method is discarded this time.



【Figure 10】Weight shifting

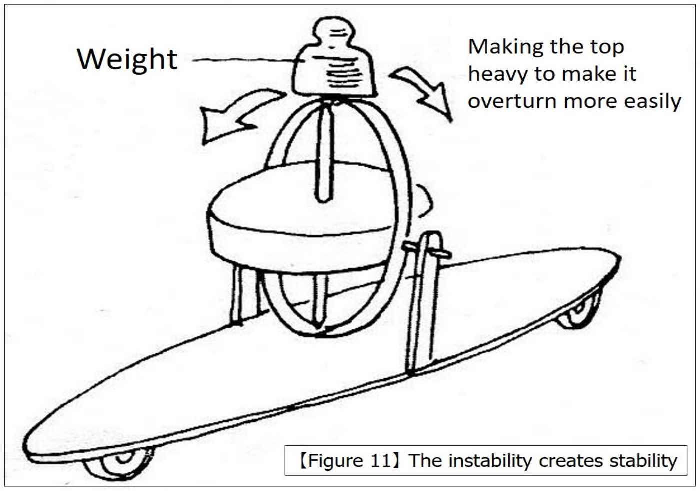
3.4.3 Positive Feedback Gimbal Control Method

The next idea is the method that goes back to the logic of the gyroscopic effect. It adds more force to the direction to which the gimbal of the gyroscope moves. It is the method to reduce the precession, and it is described as the "positive feedback" or the "negative friction" in documents that explain the theory.

The problem lies in the force application to the gimbal. Several methods are assumed here.

(1) Positive Feedback with the Potential

For the example involving the case of the vertical gyroscope, it is to set up the system with the unstable balance that is attained by placing the center of gravity above the fulcrum so that the slight perturbation of the gimbal would cause the complete flipping (Figure 11). By doing this, the "positive feedback" of gravity automatically adds force to the gimbal. What is so mysterious about this aspect is that the instability contributes to the stability of the entire system. No one can ever come up with this method just by employing conventional thought processes. Without the knowledge of the theory, no one would even try to test it.



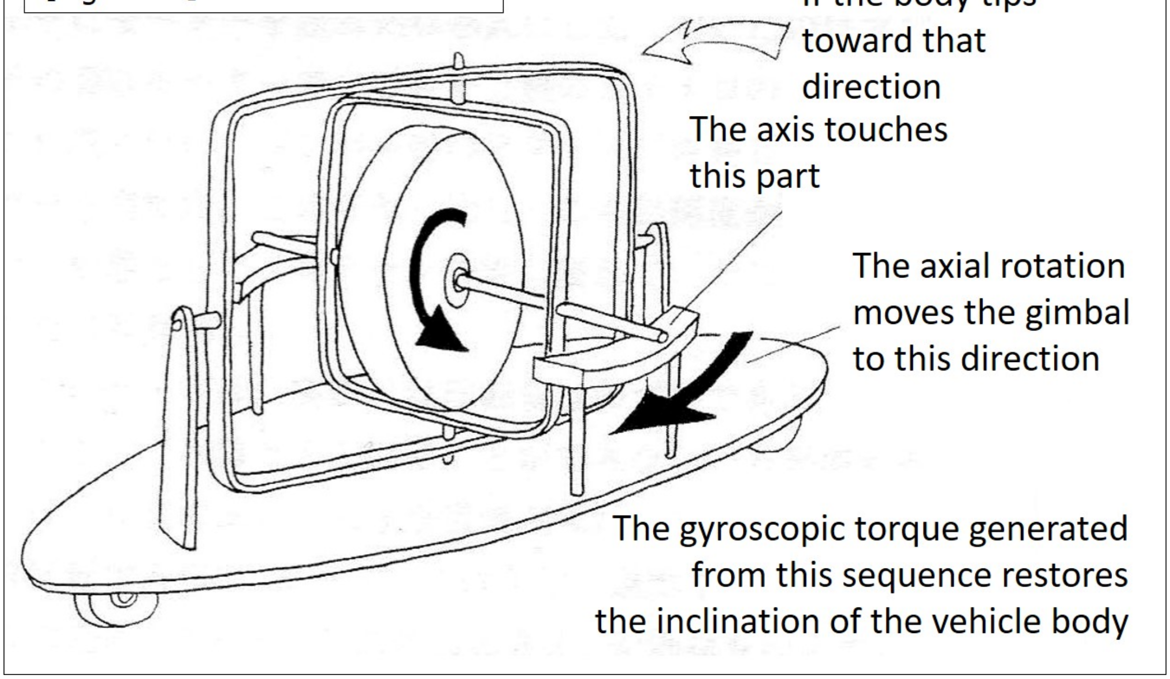
【Figure 11】The instability creates stability

About this method of utilizing the gravity, many experiments were conducted, obviously speaking. Additionally, while the mechanism that uses the springs instead of the gravity to attain the instability involving the potential energy was used, the experiments were conducted repeatedly. It eventually became clear that the experiments would not go well due to various reasons. The most significant problem was that setting up the default configuration was difficult. It is extremely difficult for models to start off from the ideally well-balanced position. Even if it seems to work well theoretically, it is left with no choice but to be deemed impractical. Still, this logic is crucially important. The point is that to attempt to support the gyroscope with the stable balance leads to the negative result in terms of the stability of the car.

(2) Positive Feedback with the Axis Friction

Next, this method was said to be used for early Brennan's models. When the car tilts, the rotational axis of the gyroscope makes contact with the chassis of the car. The resulting friction then causes the gimbal to move (Figure 12). In fact, the same type of friction is generated at the point where the axis of a spinning top makes contact with the ground, and then the forces to try to move the axis and to keep the spinning top standing upright are applied.

【Figure 12】Axis contact method



Several prototypes were made to test the method. Even though to control the gimbal had been understood to be the decisive way of solving the problem from the beginning, the practical way of how to apply the force specifically had been the issue, and the method appeared to be a good candidate. But, it was difficult for small-sized models to be used for the accurate testing. Gaining the proper friction under the vibration of the working gyroscope is almost impossible. Even if it might be theoretically possible, it is bound to be practically tricky. Brennan did not use the method in the later period of his activities.

(3) Positive Feedback with the Actuator

I wrote earlier that controlling the gimbal would lead to the solution. However, if the servomotor is directly linked with the gimbal, it would prevent the movement of the gimbal from exercising the degrees of freedom. In other words, it will be against the purpose of allowing the free precession, and end up losing the gyroscopic effect. This is the very difficult point of the issue.

A simple drawing, which is said to be used for Brennan's patent, still remains. According to the diagram, he used a pneumatic actuator for controlling the gimbal. (As a reference, Scherl adopted oil pressure for the purpose.) It was the system, in which the gimbal motion of the gyroscope was conveyed to the lever via the oil (viscous material), and the lever controlled the switching mechanism of the air valve. Just by following the pipe arrangement drawn on the diagram, it is easy to understand that the air pressure is set up to push further the gimbal toward its direction of the motion. Once the gimbal starts moving to the opposite direction, the valve will be switched and the air pressure will decrease immediately. It does not get on the way of the precession.

At first, other methods were considered and sought for. Duplicating the same mechanism on a scaled-down small model is expected to be difficult. It was destined to hit the dead end. So, I had decided to reconsider the standard, straightforward method. I went back to the theory again, and traced the equation of motion from the starting point. As a result, after all, the "positive feedback" has turned out to be the most effective.

The above-mentioned methods to use the gravity or springs turned out to be difficult to configure in the initial setting phase, because the gimbal position applies the force. As its theoretical formula indicates, it needs to use the force, generated by the "velocity" and not the "position". Moreover, it needs to use the force that points to the direction that is the same as that of the motion (negative friction). The meaning of the lever, moved by the viscous material, that Brennan once adopted lies in this "sensing of the velocity". No matter how the gimbal is oriented, the switching is done depending on to which direction the gimbal is moving. This determines the direction to which the servomotor applies the force. Under normal circumstances, the servomotor must not interfere with the movement of the gimbal. When the gimbal pushes back (when the positive or negative sign of the velocity is flipped), it needs to lose the resistance in an instant. If the gimbal's movement is disturbed (resisted by friction), the gimbal will try to lean to the direction even more, and the car is overturned easily.

There are mainly two problems for realizing the actuator method mentioned above.

The first issue involves the servomotor system. At first, a prototype that can barely be moved effortlessly with no electricity was made, with the employment of a modified servomotor for a radio-controlled model and the reduction of the number of gears. The lever of the servomotor is linked with the gimbal.

The second issue has to do with the switching mechanism that can be activated according to the velocity of the gimbal. The system to allow the sure electric contact on the switch, while a certain part moves due to the friction while slipping without inhibiting the gimbal's precession, is needed.

4. Experiment

Until the car that can run on a single rail is completed, many prototypes were made. The types of experiments being conducted are described below briefly.

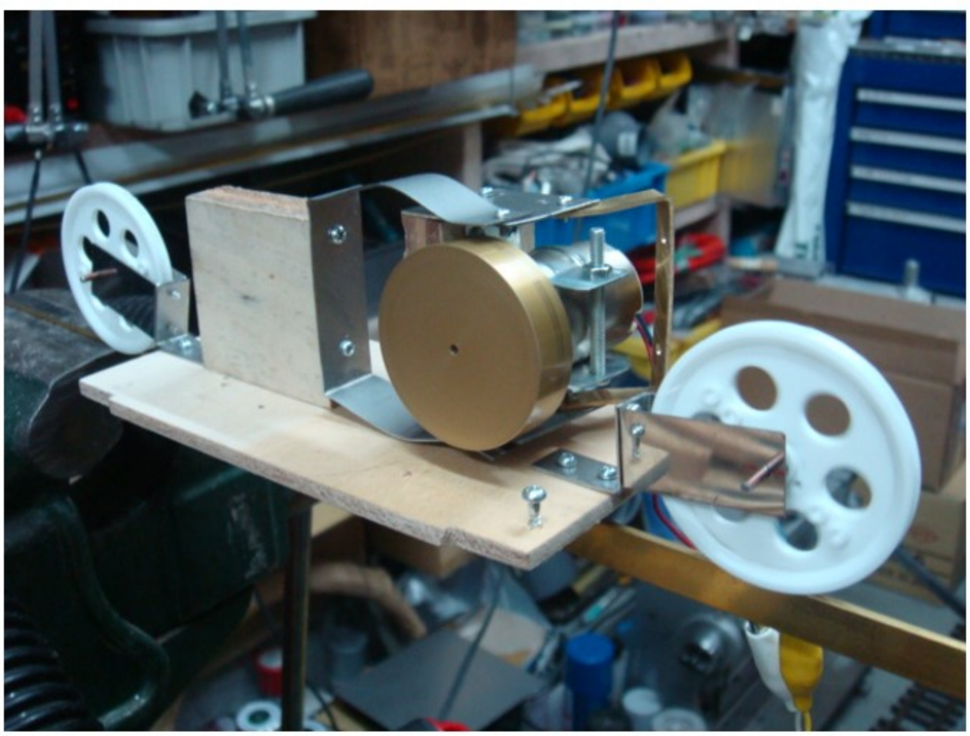
4.1 Single Gyroscope

At first, the simplest gyroscope with the single wheel was made. The heavier wheel would work to its advantage, and a brass wheel was implemented despite its high price. The first wheel was 40 millimeters in diameter and 108 grams in weight. The axis of Mabuchi 280 motor is inserted into the center of the wheel, and then it is rotated. It is possible to get the feel of the gyroscopic force, by holding the running motor with a hand and moving it.

The motor is fixed to the frame, while allowing the frame to exercise the freedom of rotational motion about the axis that is vertical to the rotational axis of the motor. This frame works as a gimbal. In order not to react to the acceleration that the car receives, the gimbal including the wheel and the motor has to maintain the momentum balance at the pivot point of rotation. The counter balance is attached, if necessary.

The experiments are repeated, by changing various conditions, in ways such as changing the angles of orientations of many attachments and changing the frictions of the gimbal pivot point.

To implement the mechanism that allows the easy adjustments of various parts with screws is advised, so that conditions can be changed without difficulty. Photograph 4 shows the Prototype No. 2, and it uses the second gyroscope. The external power source was used for No. 2, and the effect of the voltage change over the rotational speed of the gyroscope was examined. Even though the mechanism was simple like this, it can stand on a single bar if the conditions are met. This self-stability is caused by the counter torque that is created, when the car tilts to redirect the gyroscope gimbal, and the wheel's rotational axis approaches the roll axis of the car (Figure 9).



【Photograph 4】Prototype No. 2

This counter torque tends to be generated more easily, if the friction caused by the rotating gyroscope is bigger. (The friction is not with the frame, but with the "ground". In short, it is air friction.) Therefore, to increase the air resistance by letting the wheel protrude outward as much as possible and to assume the shapes that are similar to propeller or turbine blades would be advantageous to creating the counter torque. (The drawback is that it consumes the energy for rotating the wheel.) In the early stage of the experiments, there was a case in which covering the wheel with the frame resulted in the car that could not stand upright on its own. The reason is that the frame received the counter torque via the conduction through air.

4.2 Twin Gyroscope

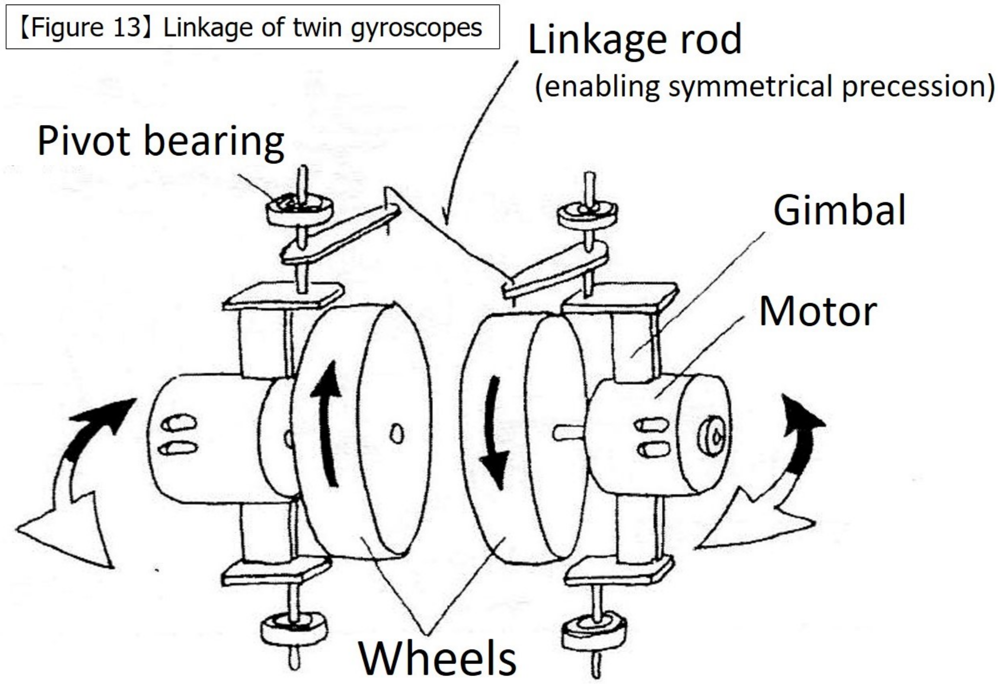
When a monorail tries to make a turn at a curve, the mechanism with which two gyroscopes rotating in directions that are opposite to each other to offset the unnecessary torque is essential. It is the case, whether the rotating axis of the gyroscope is vertical or horizontal.

For the gyroscope with the vertical rotational axis, it is easy to be misled into thinking that car is not affected when turning the curve. However, the gyro monorail running at the curve leans toward the inside of the curve like an airplane. Therefore, in addition to the rotation about the yaw axis in the horizontal curve, the car also rotates around the pitch axis as well. This is similar to an airplane trying to make a horizontal turn by tilting its body and directing its elevators to let the plane go up (from the point of view of the pilot).

When the two wheels are rotating in directions opposite to each other, both gimbals make symmetrical motions (as if they are mirror images to each other) to react to the car that is rolling (or, rotating about the roll axis of the car). As for the rotation about axes (yaw axis and pitch axis) other than the roll axis, the gimbals try to rotate toward the same direction. The movement in the same direction is forcefully prevented, and the torque is canceled. In short, the mechanism shall permit only the symmetrical movements with the mechanical linkage.

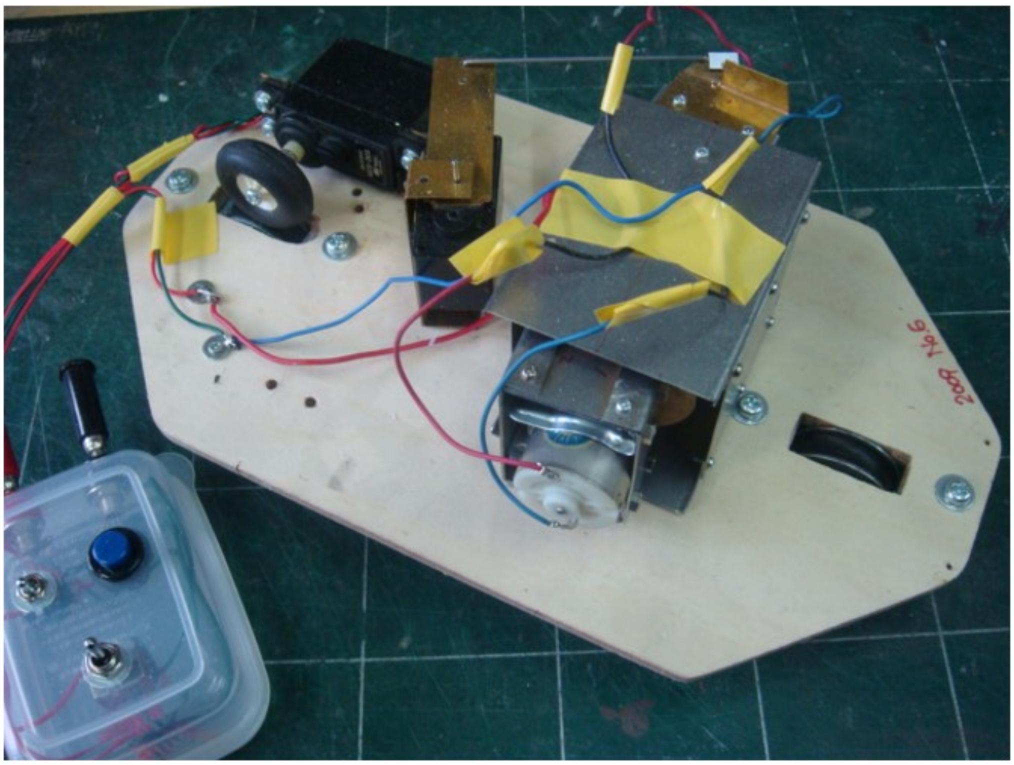
In the first prototype, both of the gimbals were connected with the linkage rod. (It was the same linkage as the one used for the longitudinal angle-tuning of the "pantograph" electric current collectors, that are generally mounted on the roofs of electric train cars.) Since the linkage rod is a straight line, strictly speaking, the both of the rotational angles cannot be identical. However, this method was adopted because it was mechanically simpler (Figure 13).

【Figure 13】Linkage of twin gyroscopes



As the gyroscope is actually made, it is accompanied with vibration that is not too weak to be noticed, due to the rotation and the reception of the lateral force, along with the precision of the wheel. To prevent the frames, pivot points, the linkage rods, etc. from dancing due to the vibration was a lot of work.

The twin gyroscopes, with two 280 motors and wheels that were 40 mm in diameter, were mounted on prototypes, from No. 3 to No. 6. The main purpose for the modifications was to experiment with the balancing systems. The gimbal control by the servomotor was adopted for the first time on prototype No. 6, and it turned out to be a major success. Looking back, this success is considered to be the most important breakthrough in this development (Photograph 5).



【Photograph 5】Prototype No. 6

An even more powerful gyroscope was required for a self-support car with batteries. Twin gyroscopes with wheels (50 mm in diameter and 168 grams in weight) that were driven by Mabuchi 380 motors of 7.2-volt configuration were made. The wheels of the gyroscopes were replaced with those of different specifications (54 mm in diameter and 236 grams in weight) in the middle of the experimental process, but the bearings of Mabuchi 380 motors were depleted in an instant. For that reason, the wheels were replaced with the lighter versions (54 mm in diameter and 208 grams in weight) and the motors were replaced with the larger Mabuchi 540 motors. No other changes have been implemented since then to this day.

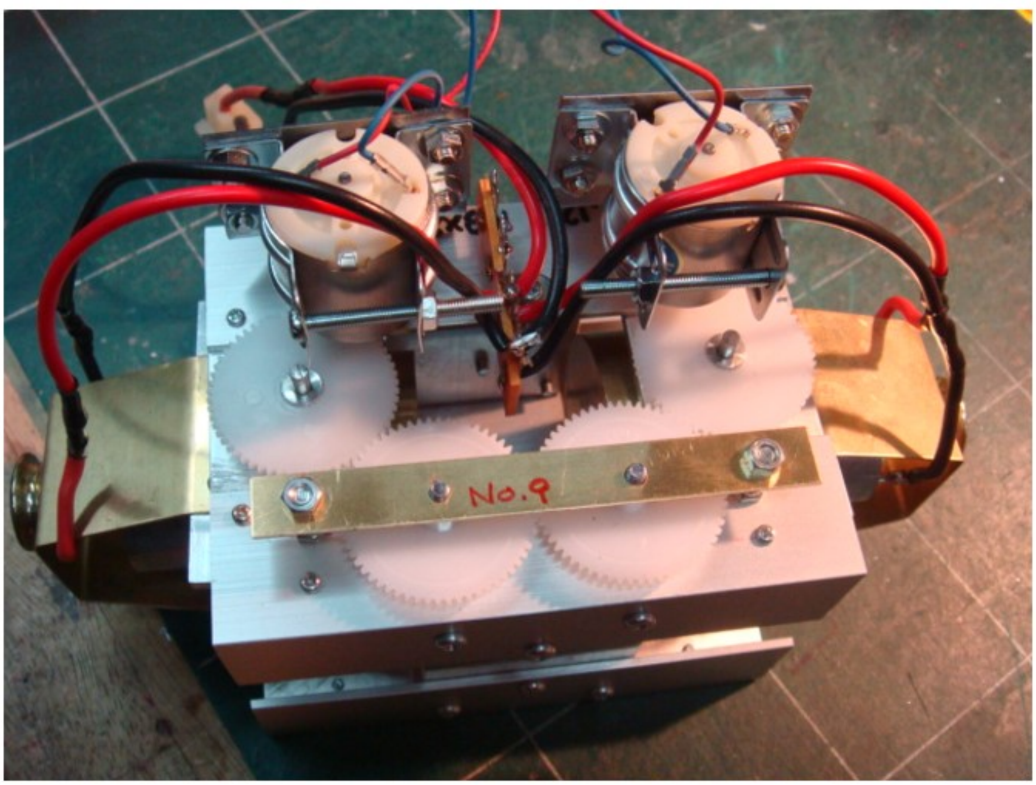
The combined weight of the two wheels was 416 grams. In Brennan's estimation, the weight of the gyroscope's wheels is required to stay within the range from 3% to 5% of the entire weight of the car. For the gyroscope in this thesis, the weight of the car can go up to approximately 8 kilograms. However, according to the intuition that is felt through the experiment, that condition is quite idealistic. Normally, the weight that is half the estimation can lie within the safe range of values. After that, the designing of the model is done while supposing that the weight of the car is set at approximately 10 times the weight of the wheel. The necessary conditions for the gyroscope's wheel will be mentioned later in this article.

4.3 Balancing System

For the balancing system, it has come down to the method of applying the rotational force directly on the gimbal by using the motor. The circuitry inside the radio control servo is removed, two internal gears are detached, and then a new lever is attached to it. In short, it is used after its gear ratio is decreased. The decision was made after getting a feel for the resistance when the electricity was turned off and the lever was moved. The first balancing system was successful in the experiment, after the method was applied.

I can theoretically figure out the servo force to decrease the gimbal's precession. However, various configuration values are required for such calculations. For that, accurate measurements are essential. To do so as a hobby is not realistic. Simpler method is to make a gyroscope first, stop the motion of the gimbal of the tilting gyroscope with a hand, and then, conversely speaking, check the reaction of the gimbal when the force is applied to the gimbal with hand to start the tilting. It is a primitive method, with which the extent of the torque and the way of the reaction to the various levels of the applied force are felt with hand, and then the gear ratio of the motor is configured based on the experience. This is the easiest way to reach the most proper configuration, after getting accustomed to it.

At first, the levers of the gimbals and the servomotors were linked with the rod. But, when the linkage between both of the gimbals of the twin gyroscope was changed from the rod to the gear, in order to pursue more accurate synchronization, the rod was removed from the linkage of the servomotors, and then the method to incorporate the motor into the gear was applied. Mabuchi 260 motor was used. Each one of them was attached on top of one of the two gyroscopes, and the pinion gear was directly applied to the spur gear of the gimbal axis. Even though the gear ratio was changed a few times, the figuration that was suited for the maintenance paid dividends (Photograph 6).



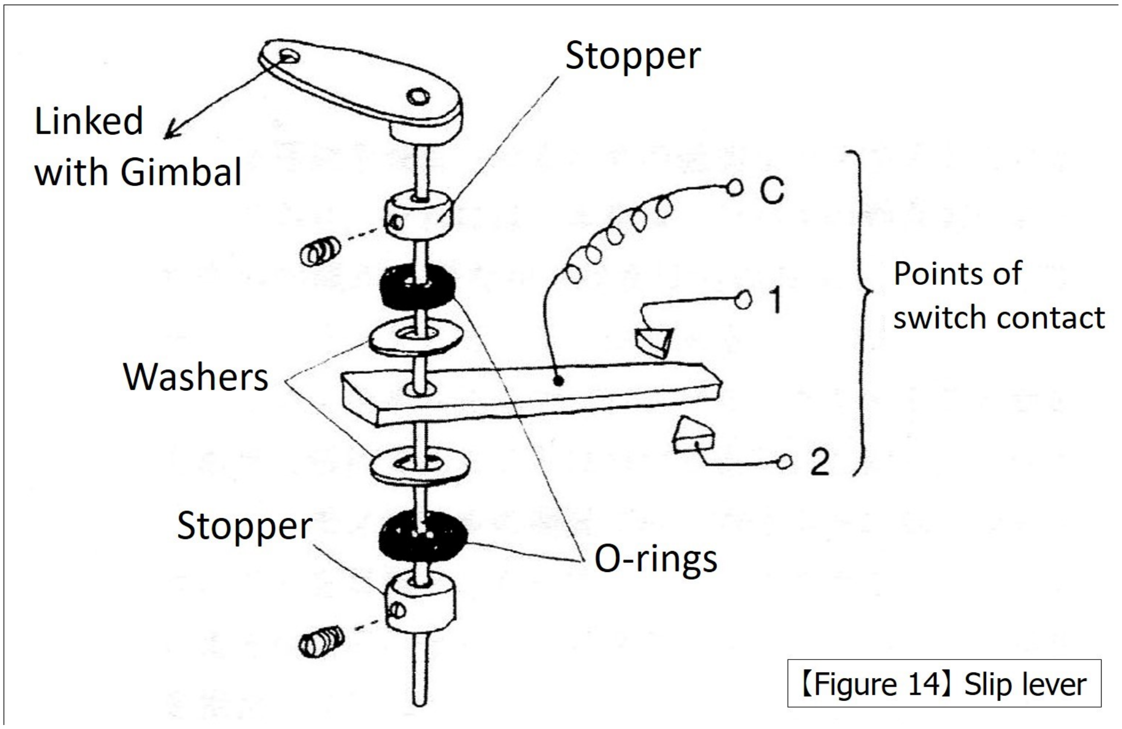
【Photograph 6】Gyro unit of Prototype No. 9

The amount of rotation for the servomotor, in fact, is limited. It hardly rotates, even with the application of the voltage. The role is just to apply the force. The motor has to withstand the extremely harsh conditions, for the electric current is big and the negative/positive currents are inverted frequently. For that reason, the motors were treated as the expendables, the less expensive versions were used, and the mechanism was designed so that the parts were easily replaceable. As a side note, when the size of the gyro motor was replaced with the larger version, the servomotor was changed from 260 to 280.

4.4 Automatic Balancing Switch

The system to automatically keep the balance is realized by controlling the switching mechanism with the motion of the gyroscope gimbal. This switch operates with the slipping lever. The friction has to work properly, and, at the same time, after making contact with the contact points, the switch has to maintain the smoothness to the extent that the motion of the gimbal is not inhibited. This adjustment procedure required great care.

In the end, the method to conduct the rotation with the friction of the metal surface that is applied with the washers and the force that is generated by the elasticity of the O-rings was adopted (Figure 14). After the trials of various methods, this method has turned out to be suitable for the maintenance and keeping the same condition of consistency for the longest period of time.

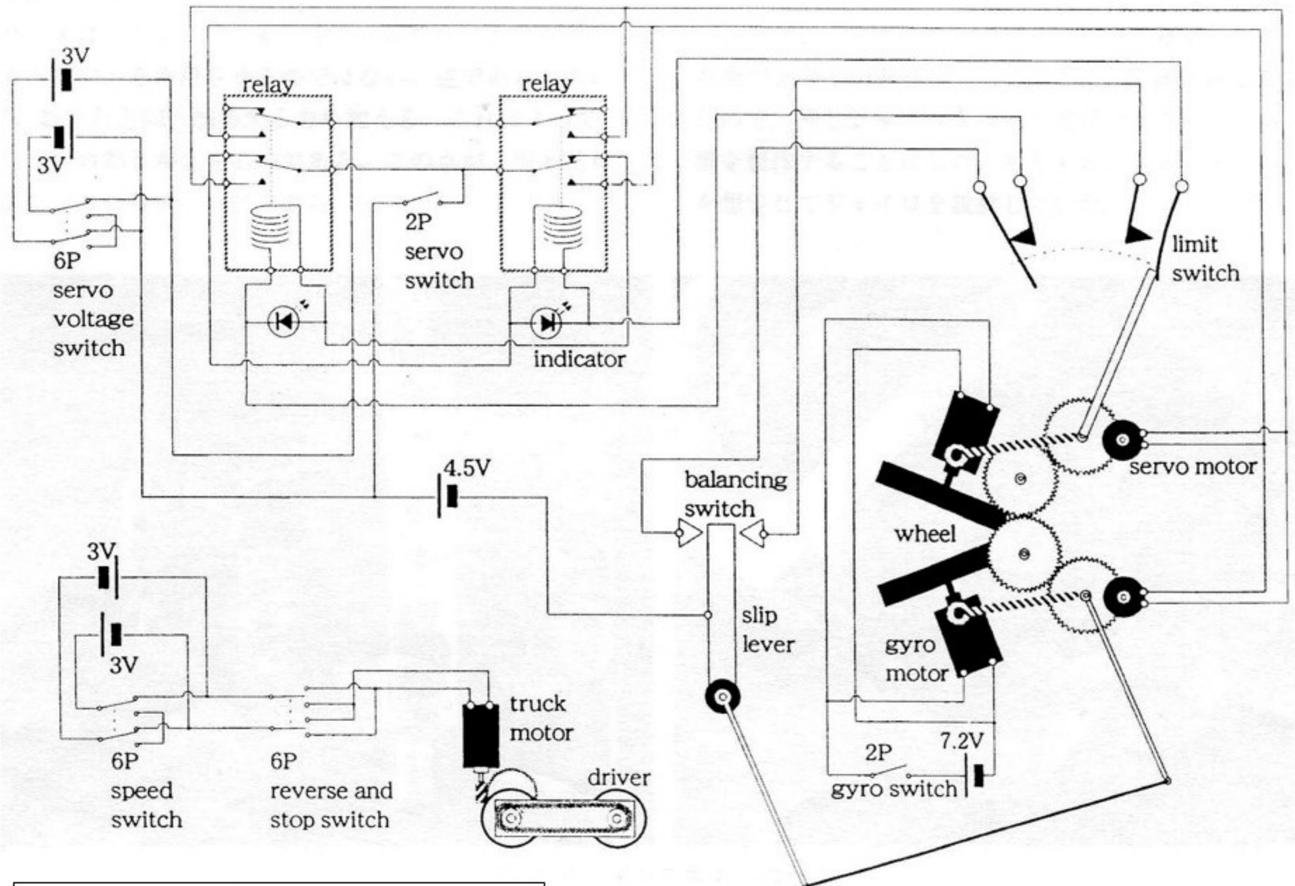


【Figure 14】Slip lever

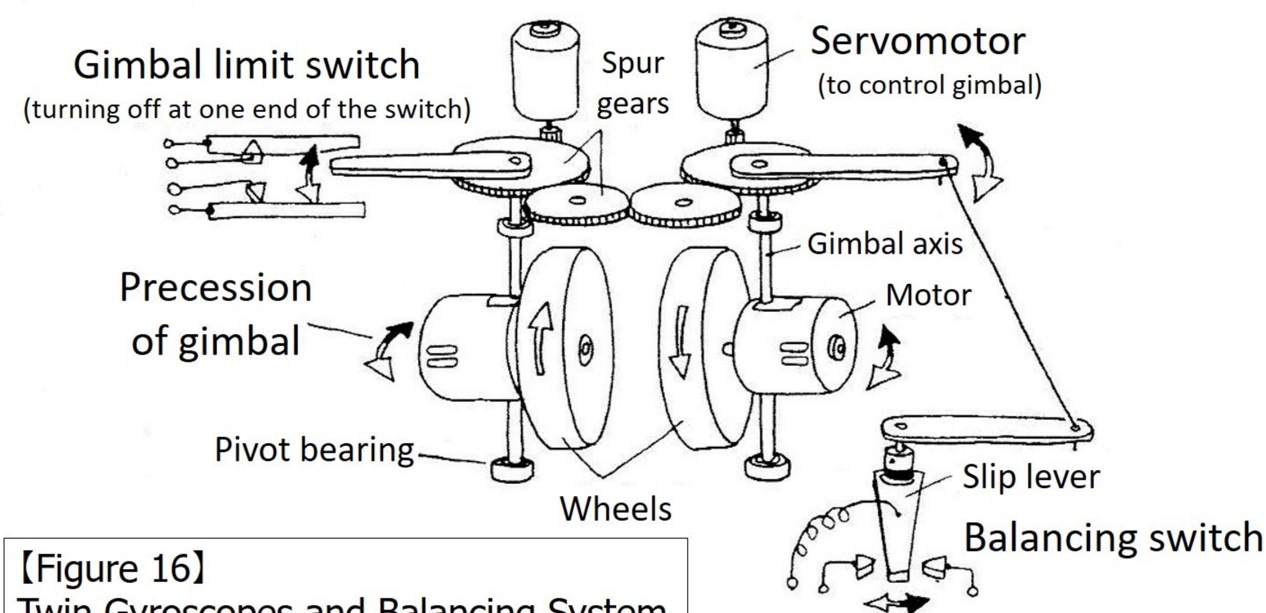
The sliding lever switches over to only one point of contact (single pole). In short, it is a three-way switch. Since the increase in the number of contact points (poles) leads to the higher difficulty in fine-tuning the mechanism, the point of contact is single (single pole). It alone is insufficient for switching over the circuit. Two small relays with double pole, double throw switches (equivalent to two, aforementioned three-way switches controlled by a single mechanism) operated with 5 volts. It switches the normal and reverse directions of the servomotor rotation, while it makes sure that one of the relays is not turned "on" when the other is turned "on". This mechanism prevents the short-circuiting when the lever and the both points of contact get too close to each other during the fine-tuning procedure. Due to the vibration of the gyroscope, accidents (overheating and leakage of the batteries, etc.) frequently occurred without the safety measure.

In addition, a limit switch that is designed solely for controlling the servomotor in the return direction when the gimbal is rotated too far to one direction (too far away from the center position) is mounted separately.

When the gimbal is positioned at the center of the mechanism, the limit switch is not thrown and the servo control is not activated. The entire circuitry (Figure 15) and the mechanism (figure 16), including the limit switch, are shown.



【Figure 15】Entire circuitry



【Figure 16】
Twin Gyroscopes and Balancing System

5. Design Condition and Adjustment

5.1 Gyroscope

First of all, the size of the gyroscope wheel becomes the issue. It becomes a tradeoff with the power of the motor. The combinations of wheels and motors listed in Table 1 are what had turned out to show the optimal results in the experiments. In any of the cases, the twin gyroscopes are used, and two pieces of the hardware (motors and wheels) of the same conditions are to be prepared, to the greatest possible extent. The wheels are attached to the motors, and then the number of rotations and the amperage are measured by using a tachometer and an ammeter. If the margin of error lies within a few percent, that would not be a problem. However, if the margin of error is by 10 percent or more, then the elimination of the causes and the replacement of the wheel or the motors are recommended. When the monorail goes around the endless loop, the imbalance is accumulated as the offsetting of the gimbal adjustment, and it causes the monorail to tilt and get overturned in the early stage of the traveling.

【Table 1】Combinations of wheels and motors

Motor		Wheel	
Model	Voltage	Diameter	Weight
Mabuchi 280	6.0 V	40 mm	108g
Mabuchi 380	6.0 V	50 mm	168g
Mabuchi 540	7.2 V	54 mm	208g

The wheel that was used in the experiment was ground from a lathe. It is important to confirm that the two wheels are of exactly the same size by measuring the size and the weight. Obviously, the ideal wheels are the ones that vibrate to the minimal extent possible after being attached to the motor and rotating.

Even though the wheel is designed to rotate smoothly under the condition of the gimbal being fixed, the gimbal tends to wobble repeatedly in reality, and a significant amount of force is applied to the axis that supports the wheel. If the wheel is directly attached to the motor, then the bearing of the motor ends up being under strain. Mainly, the strength of the motor bearing limits the aforementioned conditions of the combination.

If the independent support of the wheel itself becomes possible, then smaller motors become available. Even so, it is ideal that the wheel and the motor are rotating in the same direction. It is because the coil inside the motor is a part of the wheel. If a gear is employed to reverse the direction of the rotation, then that much of motion will be wasted as a loss. Also, if the mechanism needs to allow the gimbal to rotate, a motor that happens to let the rear end protrude outward will interfere with the frame. Even though the form in which the motor is installed in the wheel (wheel-in-motor) is ideally suited, the author has yet to try it.

Currently, the two motors are connected in parallel, to a battery power source. If one motor gets into bad condition and the rotational speed decreases, the electric current will flood into it. This is also one of the issues to be considered.

The necessary condition for the gyroscope wheel and the rotation can be calculated theoretically. However, it is not perfect, because the tentative values are used. They should be considered as rough estimates. (Even though a mathematical formula has not been planned to be used in this article, the following formula is introduced, for reference.)

$$M (r \omega)^2 > 20 \, Wh$$

Here, M is the mass (kg) of the wheel, r is the radius (m) of the wheel, ω is the speed of rotation (rad/sec), W is the weight of the entire car (N), and h is the height (m) of the center of gravity for the car.

In other words, even though the increase in the mass of the wheel can only affect the value in the formula (left side) linearly with respect to the weight of the car and the height of the center of gravity, the increase of either the "radius of the wheel" or the "rotational speed (angular velocity)", in short, the increase of the peripheral (tangential) speed, can affect the value in the formula (left side) quadratically with respect to the weight of the car and the height of the center of gravity. Increasing the diameter or the rotational speed, rather than the increase of the weight, works better and more effectively.

Needless to say, as long as the same car weight is maintained, the lower height of center of gravity works to the advantage. Then, when they have the same height of center of gravity, locating the bulk of the weight near the center of rotation will make the control easier.

5.2 Gimbal Control

It is no exaggeration to say that the setting of servomotor to apply the force to the gimbal is the key point to the success of a gyro monorail. The important points as conditions are as follows; First, the gimbal can be moved without resistance when it has no electricity. Second, magnitude of the force of the servomotor. And the third, the reaction speed of the servomotor.

As I mentioned earlier, it is easy to find the force of the servomotor by trial and error. The servo force does not work well, if it is either too strong or too weak. If the force is weak, it cannot stop the precession of the gimbal and the car tilts immediately. If it is too strong, the reactive force will become bigger and the oscillation becomes more intense.

Naturally, the proper force depends on the force of the gyroscope. If the rotation of the gyroscope weakens due to the battery drain or some other factors, the servomotor ends up being set strong, relatively speaking. This problem does not make the situation easy to deal with.

Ideally speaking, the appropriate force is applied to attenuate the precession. Theoretically, the adjustment of the force that goes along the gimbal's movement is required. But, currently, it is only about throwing the switches for the direction change of the force and the turning on/off of the force.

Obviously, programming the system with a microcomputer is the easiest solution. However, in the development of a gyro monorail this time, to design the mechanism that does not rely on electric circuitry is the objective of the project. So, the low-tech system ends up being the answer. (Semiconductor products, except for light-emitting diodes, were not used.) Come to think about it, there was no such thing as microcomputers or sensors one century ago. Still, there was enough technology to build a "machine" that had decent practical uses. Even though it is not about showing some respect for the ancient technology of yesteryears, it became the matter of enjoying the craftworks of construction while eliminating new technologies including electronics. The field of classical craftworks is not quite what the author is the best at doing, relatively speaking.

It is better to keep the play of the linkage between the gimbal and the servo to the minimum, as much as possible. The play will delay the reaction of the servo. It not only needs surplus torque but also increases the amplitude of the oscillation of the car.

For example, if a small motor is used to make a servo with a high gear ratio, both the play in the gear and the mechanical resistance during the period of no electricity will increase. It is better to use a larger motor (or multiple motors) and fewer gears. In this case, the more massive amount of electricity is required. After many attempts of trials and errors, compromises and solutions will be worked out.

Finally, although it is the repeat of what are written earlier, the most important points pertaining to the technology of gyro monorails are written once more.

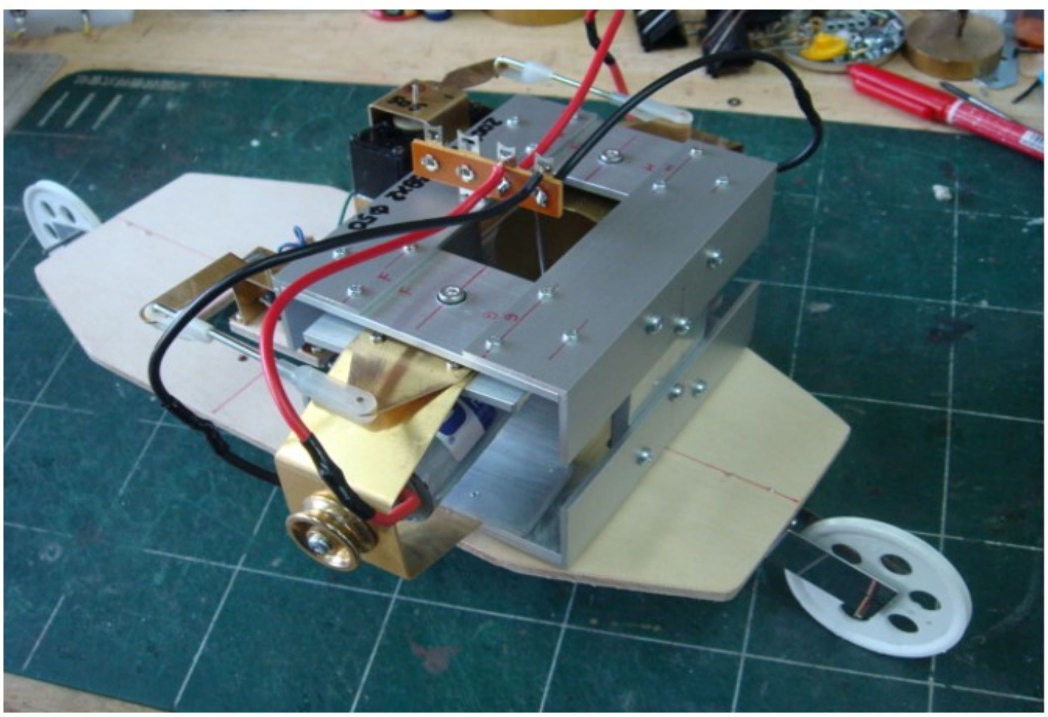
Even though the servomotor is used to stop the gimbal's motion, it does not apply the force to the direction opposite to the direction the gimbal is moving. It is actually the opposite. When the gimbal moves, the servomotor applies the force to the direction of the motion. With this method, the gimbal's motion stops. This point is the core of the technology involving gyro monorails.

Incidentally, the setting which appears to be intuitively unlikely in terms of the "engineering sense" leads to a success in gyro monorails. When only the motor of the gyroscope is stopped, and the gimbal is mobilized manually, the balancing system will work while restlessly dancing to the left and right. It cannot be stopped in the middle. This "instability" is indispensable for gyro monorails.

This is based on the same theory, in which a spinning top maintains the upright orientation by using the force of the top trying to tip. The setup that allows for easier tipping or tilting is the secret for not to topple.

5.3 Final Specification of Prototype No. 9

Prototype No. 6 was the first ever to run on a single rail, despite its being remote-controlled (Photograph 5). The subsequent models are aimed to be self-supported, loaded with all batteries. Larger gyroscopes are made, and the focus was on the experiments and development of the balancing system. Prototype No. 8 was the first ever to become self-supportive with the automatic balancing system (Photograph 7). It was not mounted with a traveling mechanism, and Prototype No. 9 that allows the traveling test to be conducted while using the same gyroscopes was being planned for being made. From the beginning, the design of the gyroscope has been done, while making the assumption that this is the size of the car.

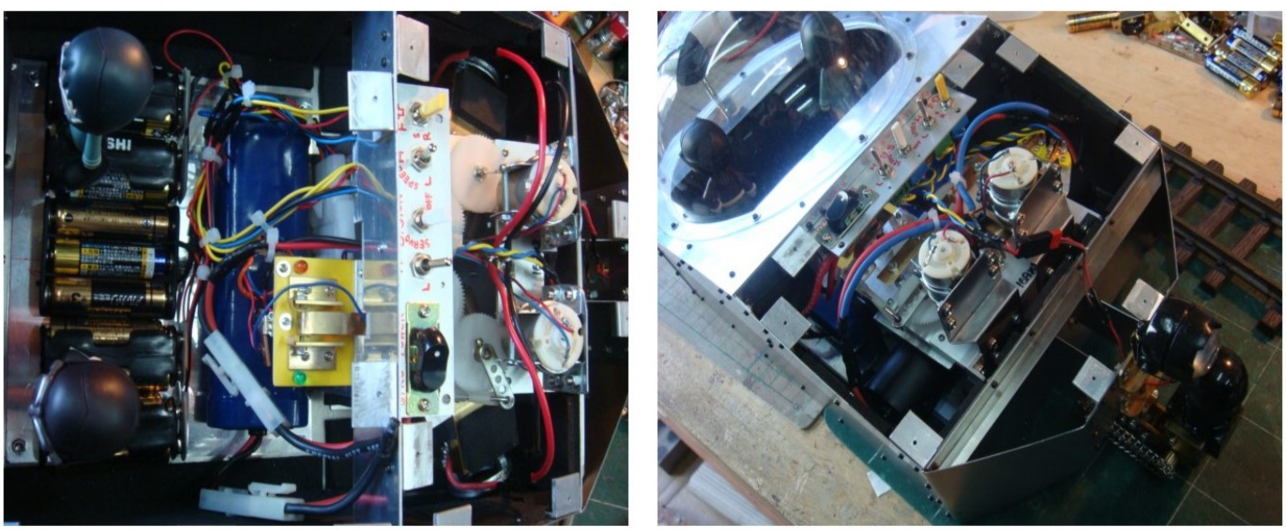


【Photograph 7】Prototype No. 8

In the middle of its assembly process, the motors and the wheels of the gyroscope were changed. The servomotors were changed, and the gear ratio was adjusted. Table 2 shows the main specifications of Prototype No. 9. The latest gyroscope incorporates the servomotors and the balancing switch in one body (Photograph 8).

【Table 2】Specifications for Prototype No. 9

●Vehicle body Length : 440mm Width : 200mm Height : 140mm Weight : 3,550g Chassis : Iron Body : Aluminum Platform : Brass	**●Traveling device** Motor : Mabuchi 260 Power source : 3V or 6V (switchable) Reduction ratio : 45.0 Driving wheel : 26mm diameter, Brass 1.5mm flange height
●Gyroscope Dimensions : 190mm X 150mm X 120mm Weight : 1,500g Frame : Aluminum Wheels : ϕ54mm 208g Brass (two) Motors : Mabuchi 540 (two) Power source : Nickel-Cadmium rechargeable battery 7.2V	**●Balancing system** Servomotors : Mabuchi 280 (two) Power source : 3V or 6V (switchable) Reduction ratio : 5.0



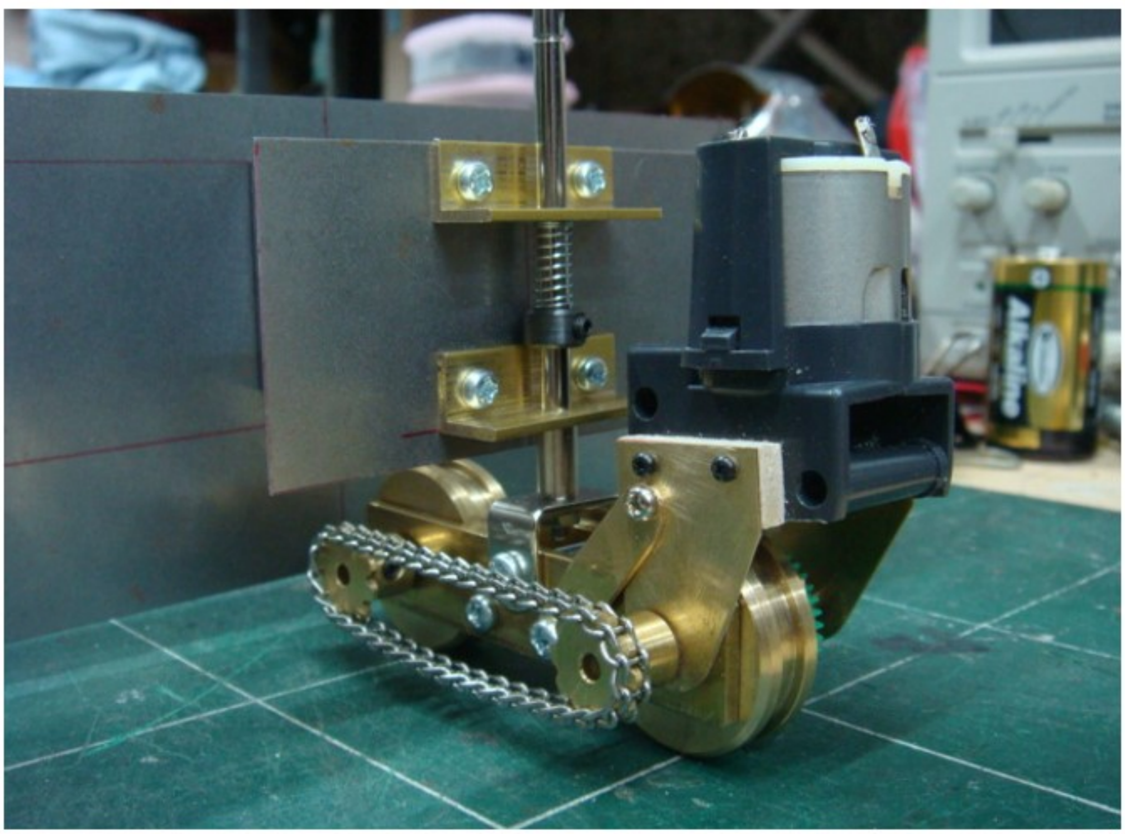
【Photograph 8】Interior of Prototype No. 9

As the remodeling and testing are repeated, the time duration for its ability to stand on its own increased gradually. In the end, it could run several laps on a loop course repeatedly. When the adjustment worked well, it did not fall down even if an object was suddenly loaded on either side of the car, for example. It automatically tries to regain and maintain the balance by lifting the heavier side automatically. Its action to naturally lean toward the direction from which it receives the forces, such as the centrifugal force or the force of the side wind, makes the gyro monorail look like a living creature.

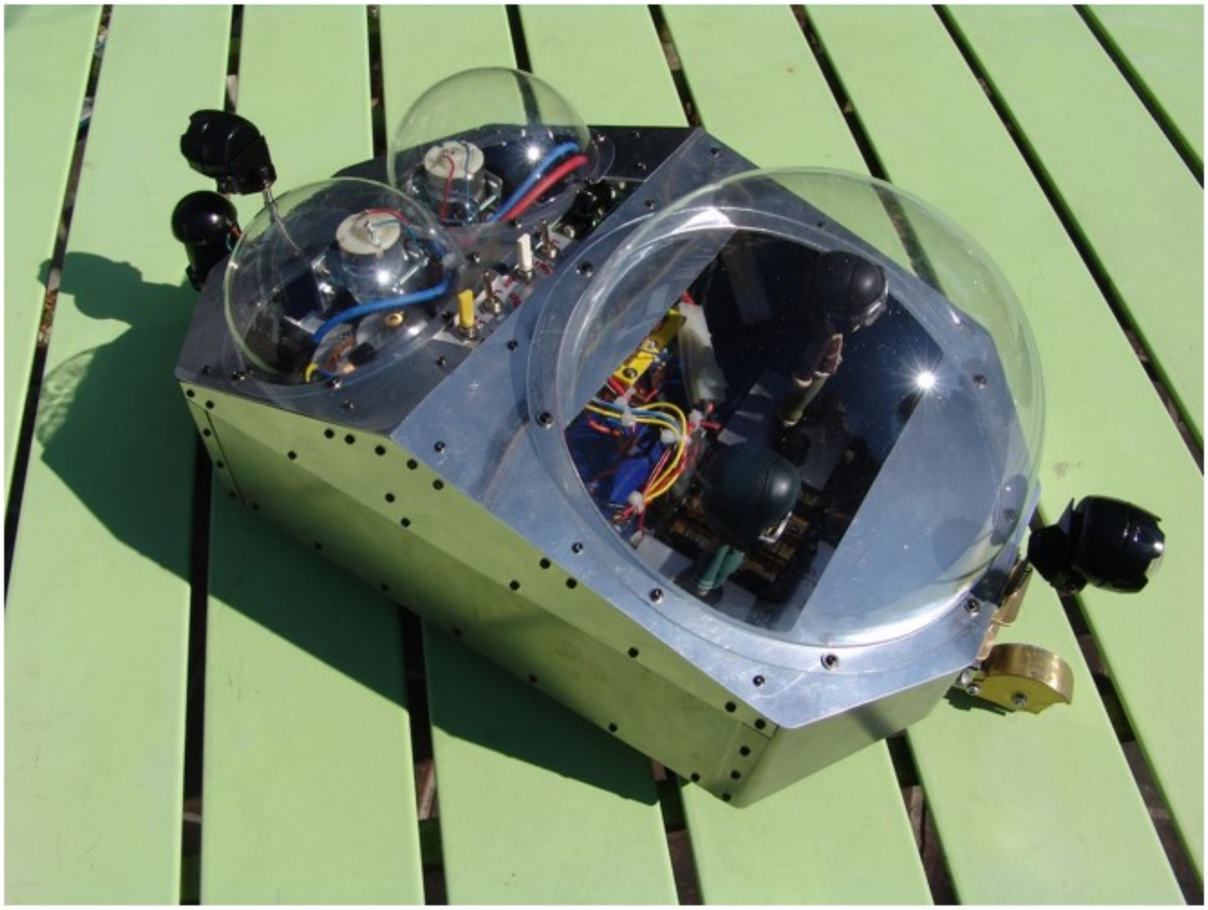
Although its body was not complete, as the video footage showing the running scene of Prototype No. 9 was uploaded on the Internet, the access count from all over the world reached 10,000 and beyond during the first 10 days. The video of a gyro monorail had not been found on the Internet until that. Hundreds of e-mails flooded into my account, and that kept me very busy with preparing several template patterns of replies and sending them. It appears that the interest for gyro monorails in general is even more intense outside Japan than in Japan.

Currently, an even larger gyroscope, which is scheduled to be loaded on the upcoming Model No. 10, is in the designing phase. The latest gyro I have is still loaded on Model No. 9, and it is going to stay there. Likewise, Model No. 6 still remains. The other prototypical models no longer exist, because their parts have been reused for other models.

Model No. 9 is the first to specifically realize the functions for a gyro monorail, and it is deservingly equipped with the dedicatedly designed body. This chassis and the platform of this car are inspired by the Brennan's model. The ways in which the Brennan's model and Model No. 9 are mounted with parts, such as headlights (A commercially available small flashlight was used.) and the traveling motor, are similar to each other. The design was originally planned to have a cabin structure encasing the gyroscope mounted in the front part of the car, and a loading platform mounted on the rear part of the car like a truck. But, the problem was that it would be too similar to the Brennan's model (It might be ideal as a model, though.). No matter how it was designed, it appeared to always end up looking like a motorboat. It was redesigned, based on the the spaceship toy, which I, in my childhood, often saw in a toy store. (I just saw it and could not get a chance to purchase it.) Although it is not yet painted as of today, it is almost complete. It is planned to be painted during the warm season (Photographs 8, 9, and 10).



【Photograph 9】Platform of Prototype No. 9



【Photograph 10】Body of Prototype No. 9

Additionally, I would like to mention that I stuffed sponge into the chassis to give the sound-insulating measure for the minimization of its noise. I received multiple e-mails from the United States, saying such things as, “Is it a shaver?”, “Would this glide on the surface to smoothen it?” I was inspired by such messages, and had decided to name Prototype No. 9 “Shaver”, not “Sabre” as for the fighter jet F-86.

6. The Problem to Solve In the Future

The problems to solve are piled up. The main problems are listed, as follows:

(1) The selection of the motor and the batteries. If possible, brushless motors are desired, for they can constantly maintain the same condition. Also, it is worth trying high-performance batteries that have become available in recent years.

(2) Systematic sophistication of the twin gyroscopes. Aiming at more rational structure, including the gear linkage, is desired.

(3) Optimization of the balancing system. The adjustment of the torque of the servomotor. Or, the idea, such as throwing the switch with smooth steps without discreteness. Would it be a good idea to stop being too stubborn for too long, and adopt the control mechanism that uses microcomputers?

(4) I want to make a gyro monorail that is large enough to allow a human to ride on it and operate it. If the author gets on it, it is not impossible to imagine that it needs not the balancing system, because the human can function as the servo. This ride will surely be exciting.

Traveling scene of Prototype No. 9

(https://www.youtube.com/watch?v=K6uEcjdjc4Q)

7. Afterword

In January, 2010, Mr. Kimio Hoshino and Mr. Akio Inoue went to the United Kingdom. They gave me a photograph of a small gyro monorail, which was made by Brennan, exhibited in National Railway Museum in York. The gyro monorail is what my prototype Model No. 9 in this article is based on.

Mr. Inoue seems to be trying to make gyro monorails once again. The very view of the well-designed red train running smoothly on a single rail has to be magnificent.

It would be our greatest pleasure, if I learn that there are those who have read this article and have made up the minds to build gyro monorails on their own. There are many unknowns and difficult parts in it. However, the more people try it, the more know-hows are expected to be accumulated more quickly. Disclosing the knowledge to the public and sharing it with the people are the fundamental spirits of “technique”, “technology”, and “engineering”.

I have been reading the magazine named “Hobby of Model Railroading” since I was 10 years old, for more than 40 years without a break. The article that has attracted my attention most was about a lineup of the special models of live steam locomotives, by Mr. Akira Mitsuya. I was amazed by how much humans would even try to make efforts to eke out ingenuity just for the sake of attempting to let the train run on the rail. At the same time, I feel that to realize such thoughts is the very splendor of manufacturing.

In fact, when I was in my 20s, I once won a prize in a contest for design layouts. I had dreamed of writing a more technically sound article. It is the reason why I have decided to contribute this article, despite the fact that the technology is not fully developed. (Written in January, 2010)

The article showing how to make Model No. 7
(aimed for simpler structures, newer than No. 9)
is featured in the other eBook titled “How to Build a Simple Gyro Monorail".

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This article first appeared on 2010 May and June issues of a Japanese monthly magazine "Hobby of Model Railroading" (published by Kigei Publishing) and was translated in 2017 for The BBB: Breakthrough Bandwagon Books.

MORI Hiroshi Works List at The BBB

The Sky Crawlers

http://thebbb.net/ebooks/the-sky-crawlers.html

The Sky Crawlers: Prologue, Episode 1

http://thebbb.net/ebooks/the-sky-crawlers-prologue-episode-1.html

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MORI Hiroshi Works List at The BBB

The Sky Crawlers: Episode 2, Episode 3

http://thebbb.net/ebooks/the-sky-crawlers-episode-2-episode-3.html

The Sky Crawlers: Episode 4, Episode 5, Epilogue

http://thebbb.net/ebooks/the-sky-crawlers-episode-4-episode-5-epilogue.html

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Seven Stories

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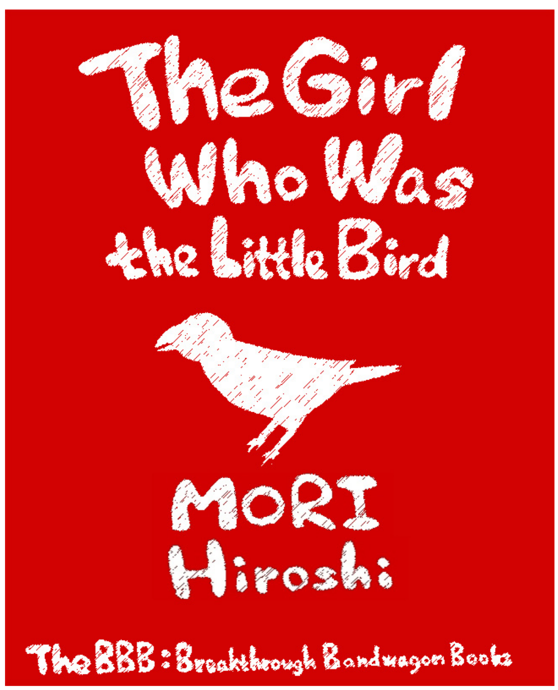

The Girl Who Was the Little Bird

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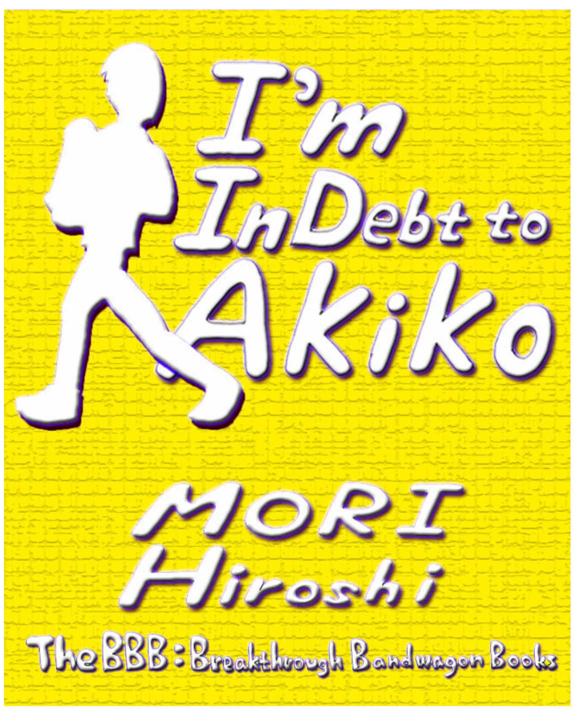

I'm In Debt to Akiko

http://thebbb.net/ebooks/im-in-debt-to-akiko.html

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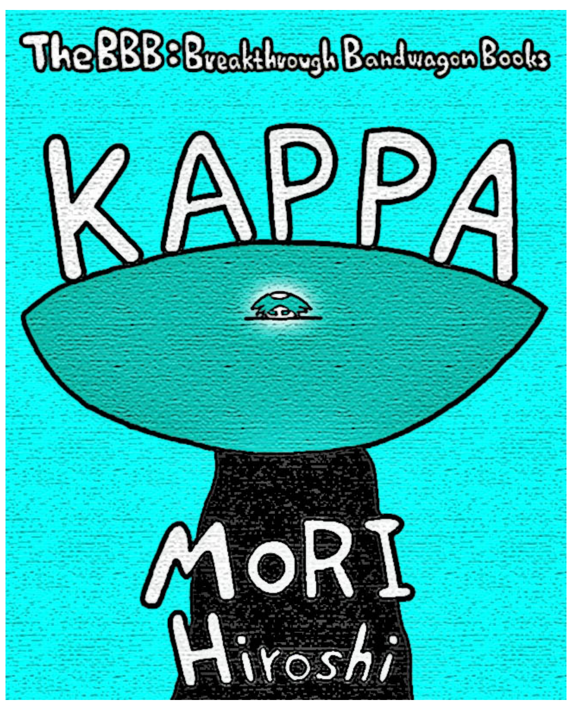
Silent Prayer In Empty

http://thebbb.net/ebooks/silent-prayer-in-empty.html



Kappa

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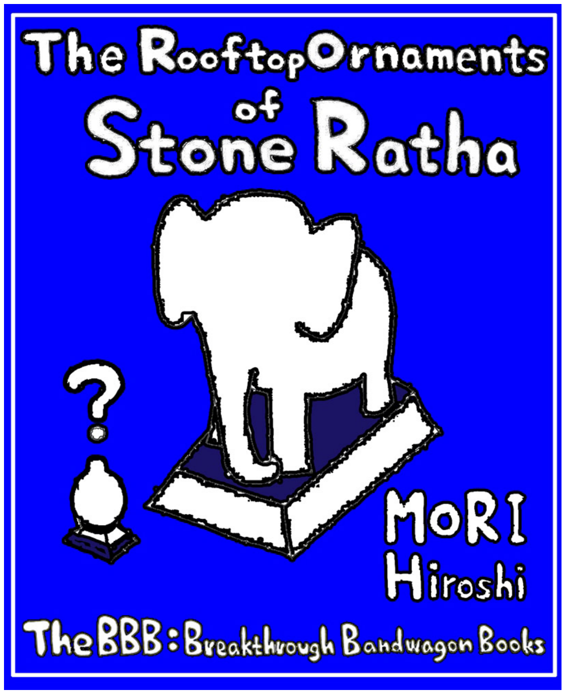
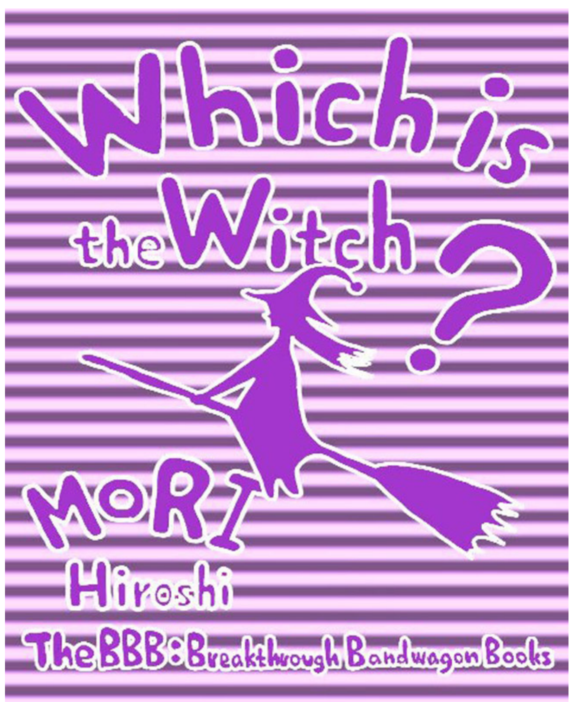


The Rooftop Ornaments of Stone Ratha

http://thebbb.net/ebooks/the-rooftop-ornaments-of-stone-ratha.html



Which Is the Witch?

http://thebbb.net/ebooks/which-is-the-witch.html
