mutual distance or spatial relation, the center of gravity of the whole composite object consisting of three different parts: A, B, and C. Then, calculating an object's center of gravity. As an example, Figure 1 portrays a proportional division is the most commonly used procedure for

2.1 Procedure by Proportional Division

2. CONVENTIONAL CENTER OF GRAVITY COMPUTATION PROCEDURE

(D3DCG).

2.2 Measurement Method of Tilt Angle and Unbalanced Load

It is practically impossible to determine the center of gravity of a complex structure with heavy weight and comprising many components by proportional division.
An effective procedure to ascertain the center of gravity is hoisting an object inclined at a specific angle with a crane and measuring the load of a grounded section together with the tilt angle, as illustrated in Figure 2. 

An angle and a load are measured by changing an inclined part and its grounded section by turns. Then trigonometric functions are applied to the result to solve it geometrically. Consequently, the center of gravity can be determined (Figure 2).

2.3 Problems of Conventional Computation Procedure of Center of Gravity

As described above, a composite comprising extremely many components such as an automobile does not allow proportional division calculation practically because the weight and the position of the center of gravity of countless components of all sizes must be known in advance. Some components, such as an engine and an EV battery, are quite large. They are constituted by many parts to have complex geometry. It is impossible to measure the precise center of gravity of each part, so that repeated proportional division using rough estimates of them will bring about excessive accumulation of errors because of the huge numbers of computations.

Accordingly, a more realistic center of gravity computation procedure is measurement of a tilt angle of an unbalanced load. However, it can only be enforced at facilities with cranes or holding equipment, such as an automobile service station. This fact implies that a trailer truck must visit a service station each time before conveyance after loading a container to compute the center of gravity. Because it is no longer possible to carry out physical distribution services in such a fashion, this procedure is completely useless at the scene of physical distribution.

3. INNOVATION OF THEORY OF THREE-DIMENSIONAL CENTER OF GRAVITY DETECTION

3.1 Application of Ship Buoyancy Principle

A ship is a large mass with a complex structure floating on the water surface. Different from an automobile that remains grounded, a ship supports its own gravity using buoyancy obtained using the volume of water displaced by the submerged part of the hull as a reaction force (Archimedes’ principle). There is naturally no independent force that supports a ship horizontally and permanently, so its dynamic balance is invariably unstable: the balance of forces acting on a ship is in equilibrium only along the vertical direction; it is indefinite in horizontal directions, even without wind or waves. Consequently, even an extremely slight disturbance on a ship (a breeze or a ripple) might trigger tilting along the horizontal directions, even without wind or waves. This pitching tends to alleviate itself by horizontal movement. Therefore, rolling is also generated successively in the body. This rolling is expressed as a circular motion in the following equation (Figure 4) as,

\[ V' = \frac{2k}{2\pi \sqrt{\frac{m}{g b}}} \]

where \( V' \) denotes horizontal shaking (rolling) frequency of the body, \( g \) stands for gravitational acceleration, \( L \) represents the height of the spatial center of oscillation of a vehicle, and \( b \) is the width of a portion supporting the weight of the vehicle from its axis of the center of oscillation.

Because \( k/m \) can be eliminated in equation (1) and equation (2) by considering it as one variable, finally, they yield the following,

\[ \frac{V^2}{4\pi^2} \]

Because \( V' \) and \( V \) can be ascertained by measurement with a body-mounted sensor as described later, equation (3) is solvable with respect to \( L \).

3.2 Reversible Detection of the Center of Gravity from Shaking an Object

D3DCG can be derived as follows according to a process explained by a researcher [2]. First, as indicated in Figure 4, movable bodies, such as a railcar or an automobile, receive disturbance from a track or a road surface during travel. Then vertical pitching occurs on elastic structures such as the suspension and tires. This is formulated as a simple harmonic motion in the following equation:

\[ V' = \frac{2k}{2\pi \sqrt{\frac{m}{g b}}} \]

Figure 4: Concept of D3DCG

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springs as an elastic body supporting the bed, costing less than about US$ 10 in all at a do-it-yourself store. Mounted in the lower part of the bed were a semiconductor angular velocity sensor (about US $4) and an acceleration sensor (about US$ 10) purchased in Akihabara, Tokyo. Their outputs were introduced to a commercially available A-D converter (about US $190), and transmitted to a PC, which computed equation (3) and displayed the result with graphical user interface. An object starts shaking by placing it on a bed and patting its upper part softly. Then computing is conducted immediately by application of D3DG. Figure 5 presents a trophy of a complex structure (proportional division not applicable) with the center of gravity properly identified. The measuring time was about eight seconds (depending on the relation between a sampling time and FFT size).

**Figure 6:** D3DG apparatus for use with human bodies

D3DG. This detection result was close to the computation result of the center of gravity by proportional division calculation conducted by measuring the weight of the cart, the chair, and the subject in advance.

4. D3DG PREVENTING ROLLOVERS OF TRAILER TRUCKS HAULING CONTAINERS

4.1 Principle of Trailer Rollover

The principle of rollover of a trailer at a curve is theoretically very simple. Any trailer has a center of gravity as portrayed in Figure 7, which is determined by the state of the container, the chassis, and the goods loaded inside the container combined. While a trailer is travelling straight because only gravity acts on the center of gravity downward, the position of the center of gravity has no special effect on its traveling safety (over speed or reckless driving excluded). However, once the trailer goes into a curve, a centrifugal force according to the radius of the curve occurs suddenly on the center of gravity. If the centrifugal force exceeds the force of gravity when the instantaneous dynamic balance is lost, then the center of gravity of the trailer immediately starts moving outward. These circumstances produce a rollover in spite of the driver’s desperate struggle (Figure 7).

Drivers who have experienced rollover accidents of trailer trucks hauling containers, whose cases were reported by mass media, stated similarly that “there is no telling why it overturned,” or “it overturned suddenly upon rounding the corner.”

**Figure 7:** Trailer rollover principle

4.2 Container Center of Gravity is Fundamentally Unknown

Since the frequent occurrence of rollover accidents in 2009, many people have advocated that “Rollover accidents are preventable if the loading state in a container is checked by opening the container door.” In reality, the problem is not so easy. Figure 8 presents the common loading state of goods in a container photographed with the door open. Cargoes on board are displaced by shaking during ocean transport every day in container transportation (Figure 8, upper left). Moreover, loading goods that are leaned on either the right or left side in a container is exceedingly common in container transportation, and is apt to cause a rollover accident (Figure 8, upper right) because commodity manufacturers carry out production in developing countries for low-cost labor and cut off physical distribution cost. The largest cost saving object is unskilled labor to load goods into a container. Native workers are employed at low pay for simple novice tasks. They often untrained. It is assumed that they would never be taught the risks of loading on one side. Moreover, it is a misunderstanding that special goods are dangerous but ordinary goods are safe. The lower left of Figure 8 depicts a container carrying only ordinary corrugated fiberboard boxes. Nevertheless, they burst and expanded rapidly out of the container as soon as the door was opened. A slogan "space is money" prevails in the physical distribution industry. Therefore, it can be readily understood that a sender wants to stuff a container to a jam-packed state, irrespective of overcharges. Contrary to the rules, the real conditions are eye-opening. A particularly illustrative example to those unfamiliar with real conditions in the physical distribution is presented at the lower right of Figure 8. Goods of various shippers and kinds are mixed in confusion and loaded in one container. This is a physical distribution mode called a consolidated container, with a huge amount of distributions. The type, shape, and weight of load differ for each shipper in one container, and the position of the center of gravity varies for each goods naturally. They are loaded carelessly in a single container.

Figure 8 illustrates a mere example of a common situation in a container in the physical distribution scene. The actual mode is an infinite combination thereof, varying day by day. If opening the door of a container can solve the rollover issue, then this paper and various technologies might be completely useless.

**Figure 8:** Goods in marine container of an infinite combination varying day-by-day

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4.3 D3DCG Application

Prevention of rollover of a trailer truck loading a container by D3DCG requires determination of the center of gravity in the manner stated in III.C.2). Because a trailer has flat springs at the rear wheels and also an air suspension system under its coupler, the assumption in Figure 4 holds well while a marine container is traveling loaded on a trailer. Accordingly, a preventive device for rollover accidents can be constructed by mounting a sensor and A-D converter as described in III.C.2) on the body, and introducing a cable to mount a display at the cockpit (Figure 9). Rollover cannot be prevented practically merely by discovering the center of gravity position. Accordingly, it is necessary that the balance calculation of roll centrifugal force and gravity be applied to the position of the center of gravity, a rollover limit velocity be computed for each curve radius, and the result be shown to a driver. A suitable calculation procedure can be chosen from various known methods for such calculation. A model might exist that combines roll tilting of the body and cant. However, actual sites of a rollover accident are curves with road conditions that cannot be specified in advance. The accident vehicles are existing vehicles made by unspecified manufacturers, with wide diversity of model and wear and tear conditions. Additionally, they carry a marine container of an unreasonable loading state described above. Then, how much applicability does a rollover limit velocity formula have if it can only be used with brand new vehicles of a specific manufacturer? Actually, any formula provides just about the same rollover limit velocity to the position of one certain center of gravity. Given those circumstances, a simpler formula is assumed to be better for a user.

The system presented in Figure 9 adopted a rollover limit velocity formula that considers a structure in which a trailer has freedom of rotation at its coupler [3].

4.4 Demonstration Experiment of Public Road Transportation of a 45-Foot Container

Figure 9 exhibits a system used in the first social experiment in Japan of public road transportation of a 45-foot container, conducted by the Tohoku Regional Development Bureau, the Ministry of Land, Infrastructure and Transport, and the Tohoku Economic Federation in November, 2010. In this social experiment, a tire manufacturer in Iwanuma, Miyagi, 50 km distant from Sendai harbor, Miyagi, conveyed a 45-foot container to be shipped to North America with a trailer truck from the factory to the harbor. Because this was the first time in Japan, and because there had been no knowledge available about the prevention of a rollover of a 45-foot container, D3DCG was solely adopted as an authorized preventive device for rollover accidents for this social experiment. The system configuration used in this social experiment was the same as that described in III.C. The system was inexpensive and exhibited ease of use with existing components.

Figure 9: Preventive device for rollover accidents of trailer trucks loading a container based on D3DCG

Figure 10 shows the graphical user interface actually displayed on the cockpit of a trailer truck during this social experiment, which indicates \( V' \) (1.612 Hz), the pitch frequency of the body, and \( V \) (0.733 Hz), the rolling frequency, selected by the system at the very moment of this display. These two values and \( b \) of the trailer used in this social experiment, 2.045 m, are substituted into equation (3) to determine \( L \), then the position (height) of the center of gravity presented in Figure 10 can be verified. \( L \) is a position from the axis of center of oscillation of the trailer (the center of the wheel axis). It can be confirmed that the sum of the radii of tires used in this social experiment, 0.5 m, and obtained \( L \) coincide with the position of the point on Figure 10 (the position of the center of gravity, about 2.5 m from the road surface).

During travel on a public road between Iwanuma and the Sendai harbor, 2010

Figure 10: Detection results of three-dimensional center of gravity of 45-foot container carrying a full load of tires

The actual system presented in Figure 10 can furthermore obtain not only the height, but the horizontal position of the center of gravity. These details are not presented herein because of restriction of space, but they are available in an earlier report listed in the references and patent-related information to be disclosed in the future.

5. CONCLUSION

Extreme low cost is the greatest benefit of the present preventive device for rollover accidents based on D3DCG. The system introduced in this paper cost only about US$ 500 for the hardware components along with commercial items, 90 percent of the cost was occupied by a mobile PC and an A-D converter, other than a sensor. It is necessary to add compensation for intellectual property rights and software copyrights at the time of commercialization. Even with such a software portion, this system can be supplied inexpensively if it could be commercialized for exclusive use with the disused parts of commercial items trimmed away for cost savings, and put into mass production. No advanced parts were used as hardware. The height of the center of gravity is obtainable merely by solving a quadratic equation, as evident from equation (3). A PC is unnecessary for calculations of this level, but an already-installed-in-vehicle microcomputer would function well. Furthermore, this system works irrespective of the trailer manufacturer and whether it is secondhand or brand-new, as apparent in Figure 9. Because a trailer can be retrofitted with this device without body reconstruction, no automobile inspection is required. The center of gravity can be detected even with a human power cart, as proved in III.C.2).

However, an unexpected problem bars the spread of this system in the automobile field, which is the reverse side of the advantage described above. It is especially important that the security of used existing vehicles be improved irrespective of the manufacturer, with no necessity of automobile inspection. After all, a user can improve the security of existing vehicles without replacing them, which permits them to have to postpone purchases of new vehicles. Because economic stagnation after the great earthquake has been exhausting the trucking industry in Japan, security improvement using existing stocks of equipment agrees with governmental policies. However, automobile manufacturers are afraid that the spread of this system might influence users to forego purchases of brand-new trailer trucks. Nevertheless, because prevention of accidents should be given top priority from the national viewpoint, this system has earned the greatest expectations from bereaved families of traffic accidents. The conquest of this dilemma might depend on circumstances surrounding rollover accidents taking place repeatedly in the future.

REFERENCES

