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Three-Dimensional Center of Gravity Detection for Trucks Hauling Marine Containers

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Abstract
Difficulty in preventing rollover accidents of marine containers derives from various load conditions of cargoes inside the containers. Heavier cargoes are widely regarded as presenting greater danger of rollover accidents. However, this presupposition is severely misleading because lighter cargoes having a higher center of gravity such as machinery with an upper mass can also cause rollover accidents. Rollover accidents are explainable fundamentally as follows.
The center of gravity of a truck loading a marine container conflicts with the centrifugal force in cornering. A truck is unstable, causing a rollover accident when the moment originating from the centrifugal force exceeds that originating from the force of gravity. Such a truck might cause a rollover accident at a lower driving speed when the center of gravity is positioned higher. The question is therefore how to find the center of gravity of trucks with marine containers. Conditions of cargoes inside the containers differ greatly. Moreover, it is practically impossible to calculate those conditions by measuring all cargoes piece-by-piece in a container unless the time and cost to do so are unlimited. Without knowing what is inside a container, there is no way to detect the center of gravity after a truck starts moving.
An important invention by the second author of this paper was produced to solve that difficulty. Detection of the Three Dimensional Center of Gravity (D3DCG) can ascertain the position of the center of gravity while trucks are moving. Soon after starting to move, vertical and rolling motions are measured onboard the trucks in half a minute. Then D3DCG is activated, instantly assessing the position of the center of gravity. D3DCG assumes that the center of gravity causes unique motions depending on its position on the truck. Therefore there is no need to know what is inside the container.
This paper first demonstrated the precision of D3DCG running an experiment by which a truck scale model was used. It was driven by remote control. Results of positions of the center of gravity delivered from D3DCG were compared to those obtained using ordinary piece-by-piece calculations. Secondly, this paper assessed examples of D3DCG installed on an actual truck loading real marine containers. Results proved that D3DCG is valuable for real-time detection of the center of gravity when driving. This achievement will greatly contribute to the prevention of rollover accidents.
***Keywords**:* Trailer, Rollover, Road safety, Vibration of moving body, Natural frequency, D3DCG

I. Introduction

A prominent problem of transporting marine containers on roads is that truck drivers do not know conditions of cargoes loaded inside the containers because intermodal contractors have limited rights to open the containers without permission by shippers of the cargoes. Furthermore, time schedules of delivering the containers to the shippers are always tightly ordered in global supply chain networks. Consequently, severe accidents involving trailer trucks, typically rollover accidents, have increased, as reported by the Sankei Shimbun (2015) and the Asahi Shimbun (2015). The center of gravity of the trailer trucks must be ascertained to prevent rollover accidents even under the conditions above by which the drivers can neither open the marine containers nor see inside them. For example, Figure 1 shows a typical rollover accident of a trailer truck loaded a marine container caused by the higher center of gravity occurred on March 25, 2014 at Tokyo Central. Regarding the official accidents reports by Ministry of Land, Infrastructure, Transport and Tourism of the Japanese Government, 16 cases of similar accidents occurred in Japan during 2014 and 2015.

The center of gravity of trucks can be measured using a truck scale such as that reported by Mikata et al. (2011) only in cases where the truck driver has sufficient time to go where a truck scale is available and sufficient funds to pay for the measuring service. Actually, this is unrealistic under actual conditions of logistics by which shippers and shipping lines order just in time delivery of their containers at minimum cost. No driver can waste time and money to find a truck scale somewhere during their busy business day.

The only way to overcome this difficulty is to introduce detection of the three-dimensional center of gravity (D3DCG) in trailer trucks transporting marine containers while they are traveling.

Figure 1: Trailer truck hauling a marine container in a typical rollover accident caused by a high center of gravity: March 25, 2014 at Tokyo Central.
Left: Aerial view of the accident site.
Source: http://mainichi.jp/select/news/20140325k0000e040216000c.html
Right: Interior view of the marine container which caused the accident.
Source: Tokyo Metropolitan Police Department

II. Detection of Three-Dimensional Center of Gravity

D3DCG can be derived as follows according to a process explained by Kawashima et al. (2014). First, as presented in Figure 2, movable bodies such as an automobile or a railcar, receive disturbance from a road surface or a track during travel. Then vertical pitching occurs on elastic structures such as the suspension and tires. This pitching is formulated as a simple harmonic motion in the following equation.

$$V' = \frac{1}{2\pi}\sqrt{\frac{2k}{m}} \tag{1}$$

Therein, V' stands for the frequency of vertical simple harmonic oscillation of a body, π represents the circular constant, k signifies the spring constant on the right/left-hand side of the body, and m denotes the body weight. 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 as

$$V = \frac{\sqrt{\frac{kb^2}{2m} - gL}}{2\pi L} \quad . \tag{2}$$

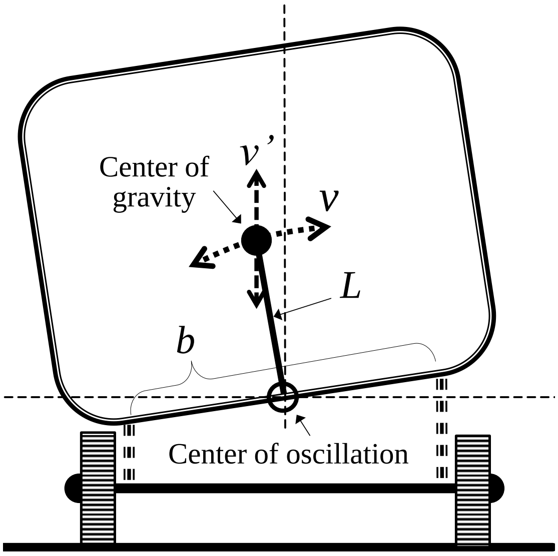

Figure 2: Concept of Detection of Three Dimensional Center of Gravity (D3DCG).

In that equation, V denotes horizontal shaking (rolling) frequency of the body, g stands for gravitational acceleration, L represents the height of the spatial center of gravity from the axis of 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. Actually, k/m can be eliminated in (1) and (2) by considering it as one variable. Therefore, they yield the following.

$$L^2 + \frac{g}{4\pi^2 V^2} L - \frac{b^2 V'^2}{4V^2} = 0 \quad (3)$$

In fact, *V'* and *V* can be ascertained by measurement with a body-mounted sensor as described later. Therefore, (3) is solvable with respect to L.

III. Accuracy of Three-Dimensional Center of Gravity Detection

3.1 Experiment Overview

Figure 3 presents a truck model to a scale of 1:14 for verification of D3DCG accuracy. First, the center of gravity of the model was measured conventionally by hanging the model from different directions. The point of intersection on hung lines represented the position of the center of gravity of the model. Secondly, a tabletop device for D3DCG was made. After the model was placed on the device, D3DCG was activated to detect the center of gravity of the model. Finally, D3DCG accuracy was verified by comparison.

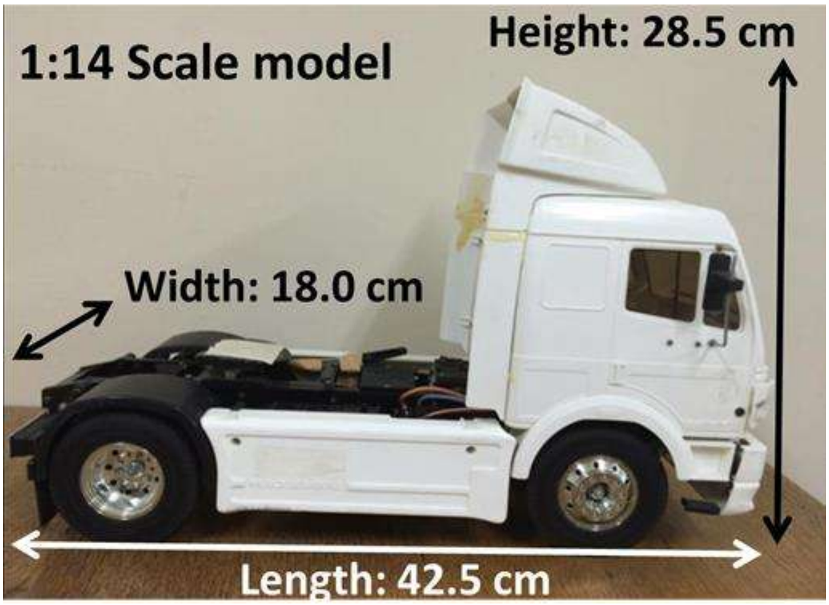

Figure 3: Model of truck to a scale of 1:14.

3.2 Conventional measurement of the center of gravity by hanging the model

A line was attached to three parts of the model: the front, middle, and back. Then the model was hung from the line. The three traces of the line intersected at a point on the model on which the center of gravity was positioned. Figure 4 presents the procedure described above. The position of the center of gravity was measured between the point and the edge of tires of the model using a ruler as shown in Figure 4. Tracing the intersection by hanging a targeted object provides the most accurate measurement to ascertain the center of gravity position. However, it is nearly impossible or too dangerous to hang heavier real trucks that are transporting marine containers. Therefore D3DCG is welcomed when the error is negligible compared to the trace of the intersection.

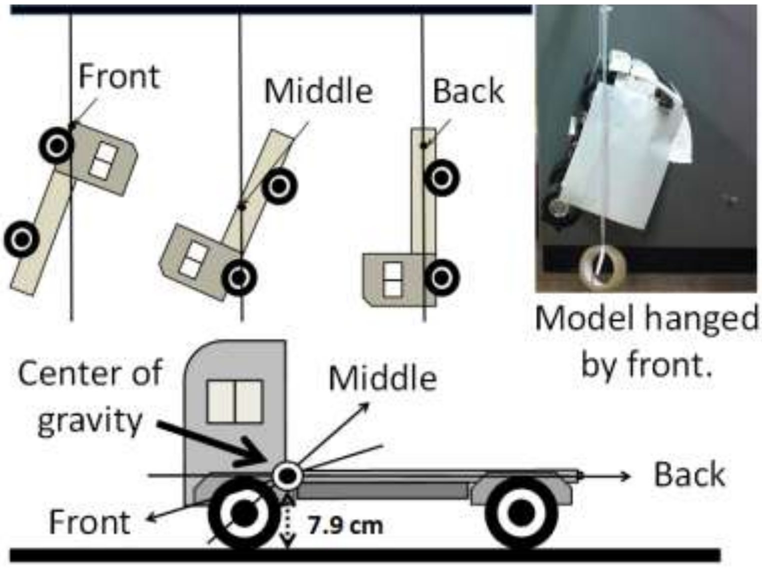

Figure 4: Measurement of the center of gravity by hanging the model.

3.3 Detecting the center of gravity using a table top D3DCG device

Figure 5 shows a table top device of D3DCG in which four coil springs are attached under a platform on which a targeted object for detecting the center of gravity is placed. A motion sensor for measuring vertical accelerations and rolling angular velocity is attached underneath the platform. Their outputs are introduced to an A–D converter, and are transmitted to a PC, which computed (3) and displays the result with graphical user interface. The object starts shaking by placing it on the platform and patting its upper part softly. Then computing is conducted immediately by application of D3DCG. Figure 6 presents a display of the center of gravity of the model by the application. The measuring time was about 8 s (depending on the relation between the sampling time and FFT size).

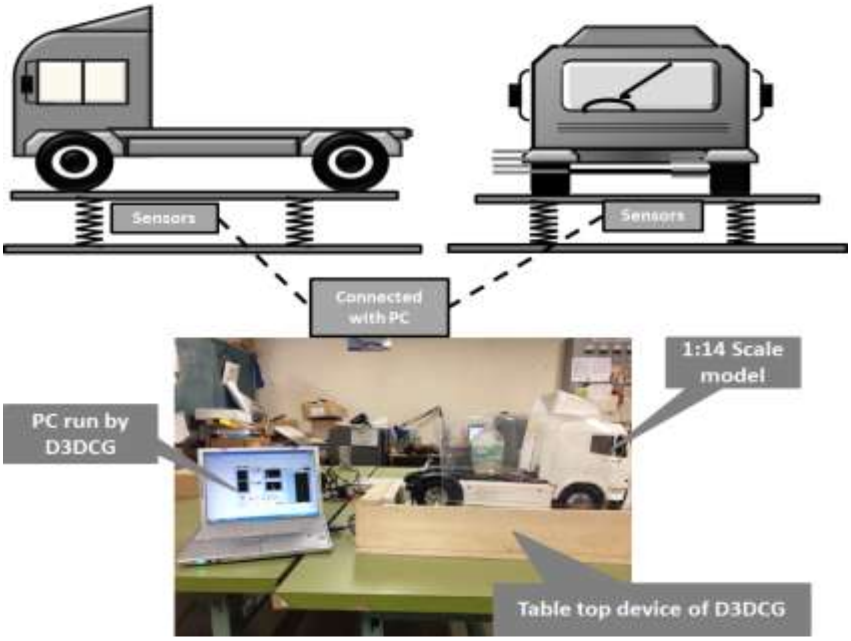

Figure 5: Table top device of D3DCG.

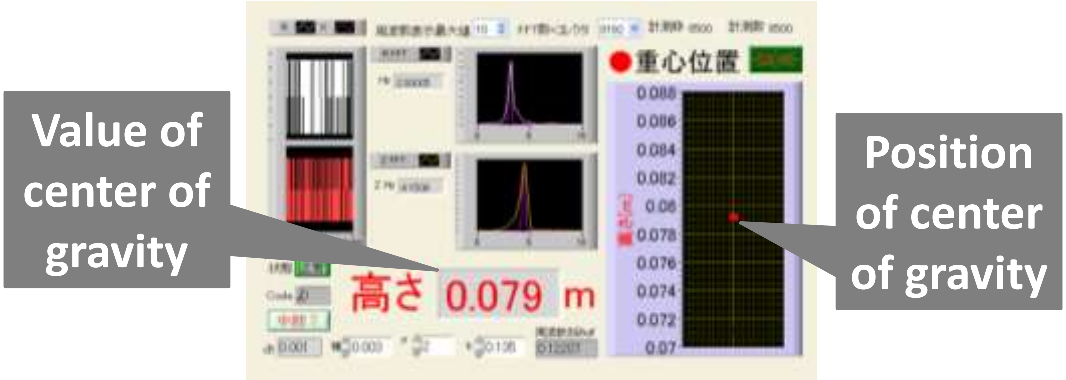

Figure 6: Application of D3DCG.

3.4 Comparison with measurement of the center of gravity by the intersection and D3DCG

Table 1 presents a comparison with measurement of the center of gravity by the intersection and D3DCG argued above. The difference between them is extremely slight. It is therefore consistent in D3DCG to detect the center of gravity accurately.

Table 1: Consistency in D3DCG with accurate center of gravity detection

Way of measuring center of gravity	D3DCG	Hanging
Measurement of center of gravity	0.0787 m	0.0790 m

IV. Measurement of Center of Gravity of Model of Truck During Traveling by D3DCG

4.1 Experiment Overview

Unlike the table top device of D3DCG, on which the ideal condition presented by (3) is available, measurement of the center of gravity of trucks during traveling by D3DCG might have errors because of various disturbances such as conditions of roads surfaces, driving speed, and conditions of steering. To verify D3DCG accuracy when it is activated during travel, the following experiments were conducted.

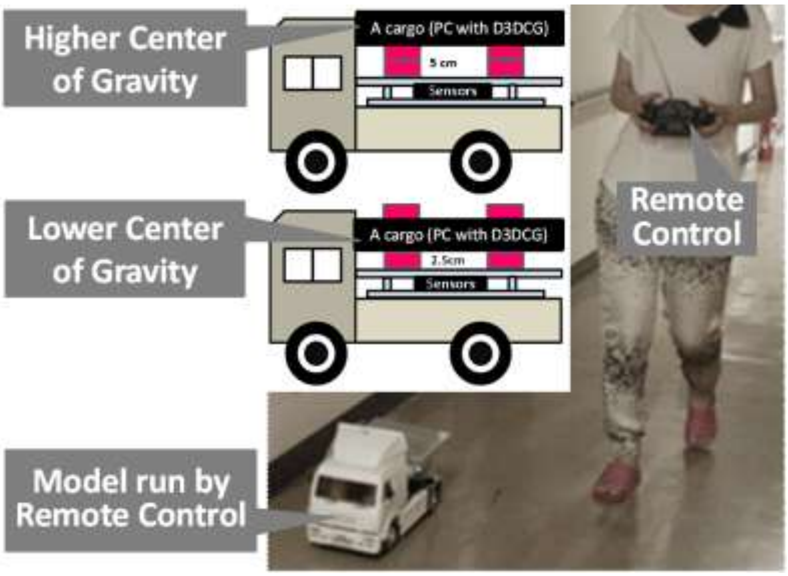

Figure 7: Mode of changing the center of gravity using a cargo and traveling the model of truck with cargo.

First, a cargo in which the motion sensor with A/D converter was attached lower was loaded onto the model as shown at the left of Figure 7. A PC on which a D3DCG application was installed was placed above the sensor; both were mutually connected. The PC can be moved vertically to two positions in the cargo so that the center of gravity of the model can also be shifted accordingly. The lower position of the PC was 2.5 cm above the intermediate platform of the cargo over the sensor. The higher one was at 5 cm, as calculated similarly.

Secondly, the center of gravity of the model with the cargo was measured using the D3DCG table top device similar to that shown in Figure 5. Finally, the model with the cargo was moved by remote control as shown at the right of Figure 7. The center of gravity was measured using D3DCG installed in the cargo.

4.2 Results obtained using the table top device of D3DCG

Table 2 presents results of the center of gravity by the table top device of D3DCG. It is apparent that the center of gravity is higher than that of Table 1 because of the loaded cargo.

Table 2: Center of gravity measured by the table top device of D3DCG

	Center of Gravity (Number of experiments: 10)			
Position of Cargo	Average	Standard deviation	Maximum	Minimum
0.0250m	0.1134 m	0.0038 m	0.1200 m	0.1080 m
0.0500m	0.1241 m	0.0039 m	0.1280 m	0.1200 m

4.3 Results by D3DCG during traveling

Table 3 presents results of the center of gravity by D3DCG during motion. Compared to the results shown in Table 2, the center of gravity is about 0.2 cm lower than those shown because that D3DCG during traveling can only detect the center of gravity from the axis of center of oscillation of the model. Judging from the value of 0.2 cm with some error, the axis of the center of oscillation of the model might be positioned at a level of the center or a bit lower part of the tires of the model. Therefore, the portion of mass below the axis of center of oscillation is not involved in the measurement. The center of gravity by the table top device of D3DCG shown in Table 2 is the height of the center of gravity from the platform of the table top device of D3DCG involving all portions of the model.

Table 3: Center of gravity measured by D3DCG during traveling

	Center of Gravity (Number of experiments: 10)			
Position of Cargo	Average	Standard deviation	Maximum	Minimum
0.0250m	0.1110 m	0.0058 m	0.1236 m	0.1042 m
0.0500m	0.1225 m	0.0098 m	0.1359 m	0.1083 m

V. Demonstration Experiment of D3DCG with Real Trailer Truck

5.1 Experiment Overview

An experiment was conducted with an actual trailer truck transporting a marine container in which imported heavier metal products had been loaded, as shown in Figure 8. Testing was conducted in Hokkaido, Japan on March 31, 2015. A set of D3DCG measurement systems, the same one described above, was installed in the truck. The sensor was fixed on a frame of the truck. A PC was carried into the cabin of the truck as shown in Figure 9. They were mutually connected by a USB cable.

Figure 8: Actual trailer truck transporting a marine container used for a D3DCG demonstration experiment.

D3DCG was activated at the cabin during traveling. The center of gravity of the trailer truck was measured in half a minute. Measurements were repeated ten times under the same driving conditions by which the truck drove straight while maintaining a constant speed.

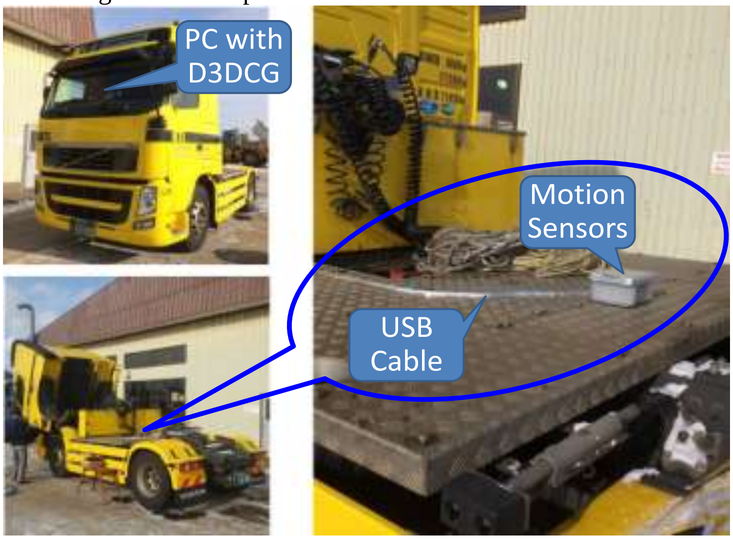

Figure 9: Installation of measurement system of D3DCG in an actual trailer truck.

5.2 Verification of Experimental Results

Table 4 presents results of the measurement of the center of gravity detected during traveling. The value of 0.675 m for the center of gravity can be used because the axis of the center of oscillation of the trailer truck should be positioned at a level around the middle part of the tires, as described in 4.3. Therefore the height of the center of gravity from ground level might be 1.225 m because the radius of tires for trailer trucks in Japan is generally 0.55 m. This value exceeds the level of the upper surface of the trailer onto which the marine container is loaded. The center of gravity of trailer trucks without marine containers is generally positioned lower than the level of the upper surface because the heaviest parts of a trailer truck, which are an engine, its parts, shaft, and wheel driving structure, are installed onto the wheel shaft of the tires underneath the surface. The marine container with loaded cargo has a lifted up center of gravity of the trailer truck when loaded onto the trailer bed. In this respect, the results presented in Table 4 are satisfactory.

Table 4: Center of gravity of a real trailer truck transporting a marine container measured using D3DCG during travel

Average	Standard deviation	Maximum	Minimum
0.675 m	0.064 m	0.752 m	0.558 m
Number of experiments: 10			

VI. Conclusions

This study demonstrated the accuracy of D3DCG in comparison with the measurement of the intersection by hanging a truck model. It also proved that D3DCG is applicable to the model during travel. Based on the results presented above, this study conducted a demonstration experiment of D3DCG with a real trailer truck transporting a marine container during travel. The result of the experiment was judged as reliable from the trailer structure and the results of model experiments.

The center of gravity detected using D3DCG should be used for prevention of severe accidents, such as rollovers, of trailer trucks that are hauling marine containers. The authors will strive to produce real-time rollover warning systems for use during travel for trailer trucks in which D3DCG can detect not only the center of gravity but also important conditions of steering related to rollover phenomena. For example, when D3DCG is used in conjunction with car navigation systems, the rollover critical speed limit can be told to drivers in real time. The analyses described in this paper are the first step to achieving such useful future applications.

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