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Design of an intelligent electronic system for dump truck tip-over prevention

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Abstract: This paper presents the basic idea behind the implementation of an intelligent electronic tip-over prevention system for a 30-tonne dump truck using a microcontroller. The objective is to design an intelligent control system to manage the stability of the truck during the dumping process. The three factors that contribute to the stability of the dump truck during the lifting process are the horizontal chassis position of the vehicle, the tilting angle of the dump bed, and the lifting speed. An intelligent tip-over prevention system has been designed and successfully tested by recording and analyzing the real-time data collected from multiple accelerometers and gyro sensors fixed on the dump bed and chassis of the truck with a feedback control for the dynamic lifting system.

Keywords: Truck stability, Truck tip-over prevention systems

Načrtovanje inteligentnega elektronskega sistema za preprečevanje prevrnite smetarskega tovornjaka

Izvleček: Članek predstavlja osnovno idejo uporabe inteligentnega elektronskega sistema z mikrokontrolerjem za prevprečevanje prevrnitve 30 tonskega smetarskega tovornjaka. Namen Sistema je zagotavljanje stabilnosti tovornjaka med odlaganjem smeti. Trije parametric, ki vplivajo na stabilnost vozila med dvigovanjem kesona so vodorovna lega vozila, naklonski kot kesona in hitrost dvigovanja kesona. Inteligenten system preprečevanja prevrnitve je bil razvit in uspešno testiran na osnovi posnetih in analiziranih podatkov večih akcelerometrov in žiroskopov na kesonu in šasiji vozila. Sistem nudi povratne informacije dinamičnemu dvižnemu mehanizmu.

Ključne besede: MOSFET; stabilnost vozila, system preprečevanja prevrnitve vozila

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1 Introduction

In developing construction areas, nonlinear soil-structure foundation is a great concern and significantly affects ground stability [1, 2, 5]. The unsaturated soil structure becomes unpredictable, especially during the rainy season. In an earth fill process, lifting a dump bed can cause the weight of a dump truck to shift to the back or tilt to either side of the truck. For instance, if one of the wheels of the truck sinks into the loosely compacted soil structure, the truck chassis will tilt to one side, causing the center of gravity of the rising dump bed to exceed the stability baseline range of the dump truck [9]. This phenomenon causes the dump truck to tip over to the side where the dump bed tilts.

Dump truck tip-over generally happens too fast for the operator to react and unlift the dump bed to a safe range. A tip-over can reach the "point of no return" in approximately 0.5 to 0.75 second and cause the dump truck to flip completely in 1.5 seconds [3,8]. An operator may take 0.5 second to realize that the truck is overturning and another 0.5 second to react to the situation. In other words, the operator takes a whopping 1 second to recognize the hazard and react to it. Given this slow reaction, the 1-second delay makes the disaster unpreventable, which poses a great danger and compromises the safety of any operator of such a machine. Therefore, to enhance the safety scheme and improve the reaction response, an intelligent detection system is necessary, which could accurately analyze the chassis horizontal position, dump bed tilt angle, and lifting speed so that an immediate response can be taken in motion planning of the lifting mechanism.

To address the aforementioned concern, various studies on dump truck stability have been conducted with the goal of creating a safety scheme during task execution [4, 6, 7]. These schemes provide the operator with a table specifying the maximum angles they can lift the dump bed for a particular chassis tilt angle. The operator refers to the table and estimates the angle independently. These techniques require a manual control system used by skillful operators. Given the hazardous situation in a real construction site, operators may have difficulty in maintaining a standard and consistent performance [10]; thus, research on electronic monitoring and detection systems is essential. In the proposed system, the accelerometer and gyro sensor technology was used to perform chassis lateral position tracking, dump bed tilt angle sensing, and dump bed lifting speed recognition, as shown in Fig. 1.

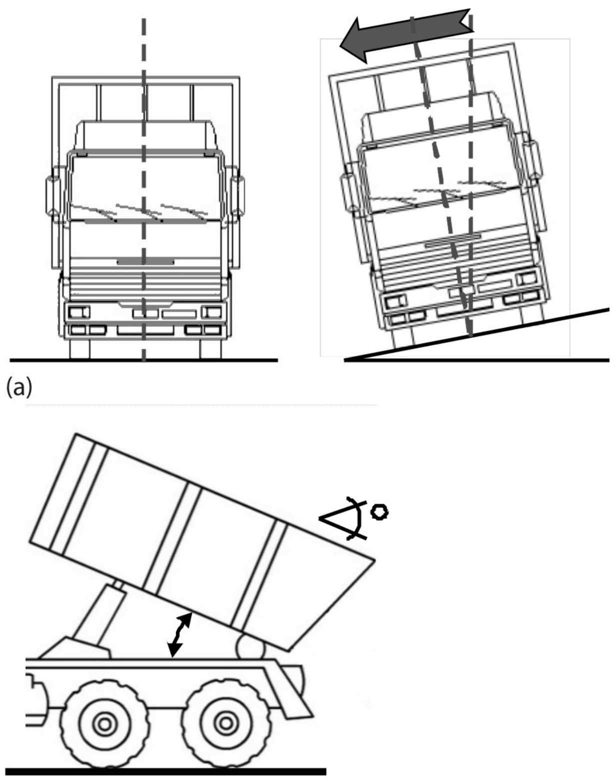

Figure 1: a) Chassis position tracking, b) Dump bed tilt angle sensing.

In this study, the proposed intelligent stability control system consists of four sub-systems: 1, 2, 3, and 4, as shown in Fig. 2. Sub-systems 1 and 2 are the truck chassis lateral position tracking and the dump bed tilt angle measurement systems, respectively. The data collected from sub-systems 1 and 2 are processed by sub-system 3, which is the microcontroller-based data processing system. Sub-system 4 is the dump bed hydraulic shaft controlling system.

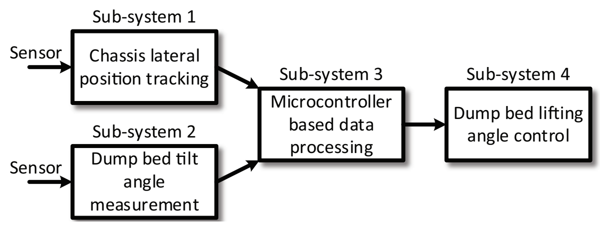

Figure 2: Sub-systems.

Both the truck chassis and dump bed measurement sub-systems are equipped with an accelerometer, gyro sensor, and microcontroller. Every sub-system works independently and performs data sampling, analog-to-digital conversion, and noise filtering. Data collected from sub-systems 1 and 2 are sent to sub-system 3 for processing. After processing, the control signal is fed back to sub-system 4 to control and adjust the speed and direction of the dump bed lifting actuator of the truck accordingly.

2 Measurement of chassis horizontal position, dump bed tilt angle, and lifting speed

The positioning systems examined in this study are as follows:

1. Dump truck chassis positioning – Dump truck chassis position is measured with reference to the initial orientation of the gyro sensor that has been set on flat ground.
2. Dump bed tilting measurement – Relative positioning and incremental positioning. This type of sensing can provide accurate positioning of the dump bed relative to the truck chassis.
3. Lifting speed measurement - Relative positioning

The horizontal position of the truck chassis is determined using a gyro sensor, such that a signal from the gyro sensor is read and compared relative to the ground. Initially, the horizontal position of the chassis should be at planar or near planar condition; then, a set of vector parameters is defined to determine the horizontal position. The lateral position of the chassis is checked before the dump bed is lifted to ensure that it is at the same height and that no tilt occurs. When the dump bed starts to tilt, the center of gravity of the region shifts accordingly; thus, the values of the current tracking position is compared with the previous tracking values to determine the next tracking position. The forces for each axis component from the accelerometer are given by

$$R_x = \left(\frac{AdcR_x \times \dfrac{V_{ref}}{value_{\max} - V_{zeroG}}}{sensitivity} \right)$$

$$R_y = \left(\frac{AdcR_y \times \dfrac{V_{ref}}{value_{\max} - V_{zeroG}}}{sensitivity} \right)$$

$$R_z = \left(\frac{AdcR_z \times \dfrac{V_{ref}}{value_{\max} - V_{zeroG}}}{sensitivity} \right)$$

where R_{x}, R_{y}, and R_z are the force vectors in the x, y, and z axes, respectively; *Adc* is the analog-to-digital conversion scheme; *Vref* is the reference voltage; *valuemax* is the maximum value for a particular AD converter; and V_{zeroG} is the reference voltage at zero gravity. The integrations of the gyro sensor and accelerometer are used to improve the dynamic tilt angle detection efficiency. The positioning of the truck chassis and dump bed angle are captured by examining the three-dimensional position of the tracking targets. A high-speed microcontroller is used to calculate the complexity of the dynamic data.

Only the dump bed is supposed to tilt throughout the dump bed lifting process. The horizontal position of the truck chassis should remain unchanged, and the value of the gyro sensor should be maintained at horizontal planar value because no tilting of the truck chassis is allowed. The microcontroller immediately recalculates the chassis angle when the value of the accelerometer varies. The angle can be calculated as follows:

$$A_{xr} = \arccos\left(\frac{R_x}{R}\right) \quad A_{yr} = \arccos\left(\frac{R_y}{R}\right) \quad A_{zr} = \arccos\left(\frac{R_z}{R}\right)$$

where A_{xr}, A_{yr}, and A_{zr} are the angles between the force vector R and the x, y, and z axes. After the movement of the truck chassis is detected and the tilt angle is calculated, sub-system 3 analyzes the situation. The data are then compared with the lifting speed of the dump bed. The dump bed tilting angle and lifting speed can be measured as follows:

$$Rate\ A_{xz} = \frac{\left(Adc\ Gyro_{xz} \times \dfrac{V_{ref}}{value_{\max} - V_{zero\ rate}} \right)}{sensitivity}$$

$$Rate\ A_{yz} = \frac{\left(Adc\ Gyro_{yz} \times \dfrac{V_{ref}}{value_{\max} - V_{zero\ rate}} \right)}{sensitivity}$$

where *Rate* A_{xz} and *Rate* A_{yz} are the rotation of projections of the R vector in the XZ and the YZ planes, and $value_{max}$ is the maximum value for a particular AD converter. A control signal is issued to slow down the lifting speed when the tilting of the chassis does not exceed the safety range from the center of gravity. However, when the value touches the boundary of the overturn range, the lifting process must be halted immediately and the delifting process must take over.

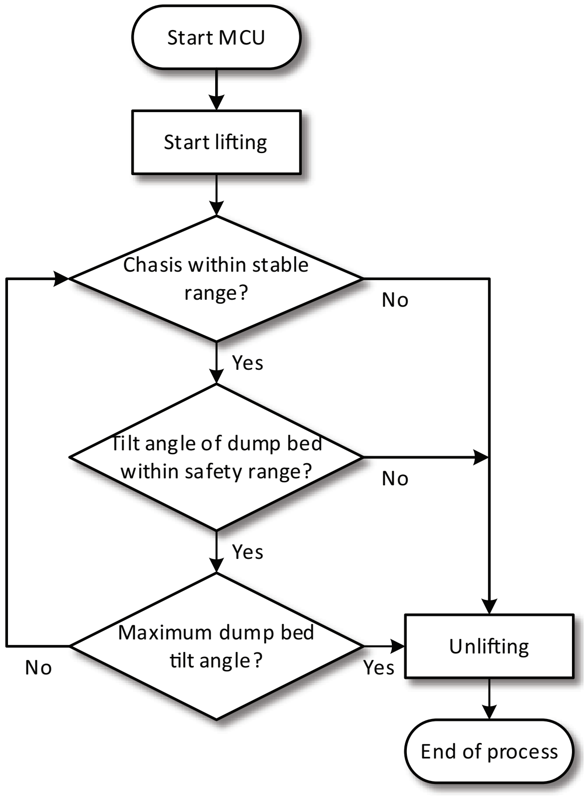

Figure 3: Process flow diagram.

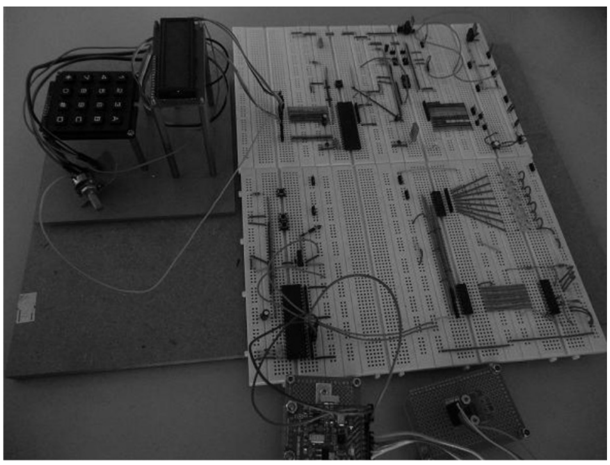

Figure 4: Proof-of-concept implementation.

Figure 4 shows the detailed hardware setup. Reference points are compared with the preset schemes. Based on the feature error of comparison, the microcontroller generates an error signal and sends the control command to the USB I/O card for interfacing with the hydraulic pump control system. In this theory, several assumptions are made as follows:

1. The hydraulic pump stops instantaneously when the stop command is sent to the hydraulic controller.
2. The vibration of the dump truck is in a known range.
3. The microcontroller response is significantly faster than the gyro sensor response.

3 Tip-over range detection algorithm

Sensor systems must have fault-tolerant and real-time capabilities. A tip-over safety range is derived and shown in Figure 5. The reference load is an 18-tonne weight carried on an 11.9-tonne truck chassis. The stability range is divided into three regions: safety, quasi-safe, and dangerous. The quasi-safe region is where the combination of truck chassis tilt angle and dump bed tilt angle causes the center of gravity to be extremely near to the boundary of the stability baseline of the dump truck. The microcontroller from sub-system 3 analyzes the readings from sub-systems 1 and 2 to determine the stability region of the overall truck position.

According to the proposed scheme, the truck lifting is at its maximum speed, which is 4°/sec, when the truck is in the safe region. When the truck reaches the quasi-safe region, the lifting process is slowed down to 1°/sec. The lifting process is stopped immediately and the delifting process takes over when the truck touches the dangerous cross over line.

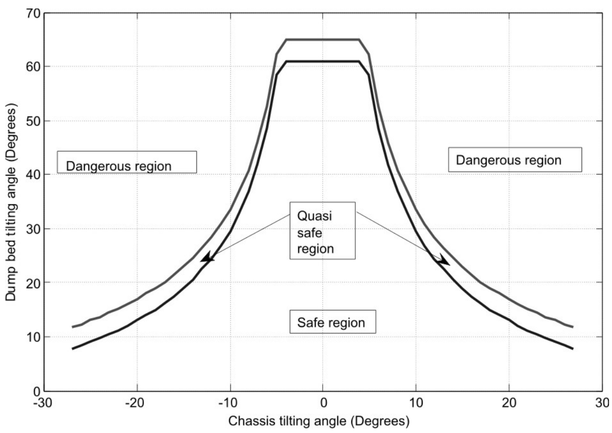

Figure 5: Safe, quasi-safe, and dangerous regions.

4 Implementation of real dump truck system

The lack of commercially available dump truck tip-over electronic sensing and control system motivated this study. Given that operating the dump truck usually involves hazardous conditions, the tip-over prevention system must be able to process real-time input and output data with minimum latency. The data are collected from sub-systems 1 and 2 where the influence of noise is addressed. Sub-system 3 should possess high computational data throughput. The system should be robust and compact enough, as well as efficient, so that it can be attached to the available onboard truck system.

4.1 Electronic circuit design

A low noise gyro sensor with Kalman filtering is selected for the axes sensing part. The model used in our system is the MPU3300-gyroscope from InvenSense, which is equipped with a 16-bit analog-to-digital converter for digitizing the gyroscope outputs. The I^2C protocol is used as the communication protocol among the sensors and microcontroller sub-systems. The following features are embedded in the intelligent detector system for robust control:

- Automatic connection and disconnection
- Estimation of system positions
- Presentation of graphic image on LCD

The output from the detection system is connected to the hydraulic lifting system. To ensure safety, the dump bed lifting process rechecks every sensor when the operator starts the lifting process. If any sensor has malfunctioned, the system triggers an alarm and automatically informs the operator and switches to manual mode.

4.2 Communication protocol among sensors and microcontrollers

A synchronization approach must be applied for designing applications that collect data from the gyro sensors and accelerometers. The combination of such a system allows applications to request data synchronously. A microcontroller management system functions as a master process on the host that connects the sensing sub-systems and a lifting control system together. During the communication, the master and slave can be the receiver and transmitter, and the data transfer can be bi-directional (full duplex). The system clock is independent because each of the sub-systems are self-clocked and synchronized by the falling edge of the master controller. The details of the manager will be described in another paper; thus, the capabilities of the manager are only listed in this paper as follows:

- Microcontroller node sharing among multiple subcontrollers
- Programming interfaces to access the submicrocontroller systems
- Dynamic network configurations without stopping any application

Figure 6: Implementation on truck.

5 System analysis and performance evaluation

A test area was constructed to evaluate the response of the tip-over prevention system of the truck. In this experiment, the truck chassis is initially set to a certain tilt angle; then, the fully loaded dump bed is lifted and measurements are conducted to observe the maximum angle of the tilting dump bed before the unlifting process. An excavator is used to pile up a slope with a certain tilt angle that mimics the real construction site, and the truck is driven onto the slope. During the testing stage, the entire system performs in automatic mode after the lifting button is pressed by the operator. The operator then leaves the truck to avoid any accident.

The experimental slope is rebuilt for every particular angle. A total of 55 experiments have been conducted. The angles are from −27 degrees to 0 degree and from 0 degree to +27 degrees. The negative degrees indicate that the truck is tilting to the left, whereas the positive degrees indicate that the truck is tilting to the right. The truck chassis tilt angle is increased by 1 degree for each of the subsequent experiments.

The experiment established demonstrates how closely the reaction of the tilt angle of the dump bed correlates to the dump truck chassis position in space. All of the components are integrated into a circuit board and constructed in an onboard embedded system. Two experiments have been conducted to evaluate the system. The first experiment tests the angle at which the dump bed tilting speed slows down upon entering the quasi-safe region. The dump bed lifting speed is initially set to its maximum lifting speed, which is 4°/sec. The dump bed rising speed and angle are monitored and recorded. The output response graph in Figure 7 shows the angle of the dump bed at the point where the lifting speed slows down to 1°/sec. The second experiment is executed in the quasi-safe region, where the dump bed lifting speed is 1°/sec. The second experiment tests the angle at which the dump bed lifting speed changes from 1°/sec to 0°/sec.

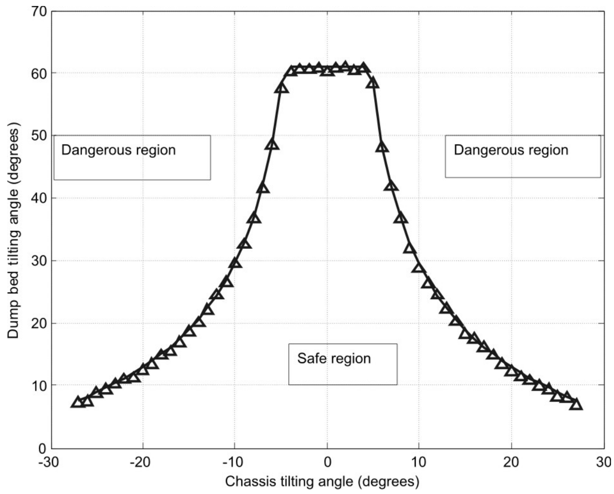

Figure 7: Points at which the rising speed of the dump bed slows down.

The output response graph shows that the real experimental results obtained from the control system of the decrease of dump bed lifting speed match the simulated data from the proposed scheme. This finding indicates that the dump bed lifting mechanism can have a smooth transition from the safe region to the quasi-safe region, which is proven in Figure 8 where the error between the real experimental result and the simulated data is less than 1 degree.

The output response graph shown in Figure 9 indicates that the real experimental results obtained from the dump bed stopping angle are extremely close to the crossing line of the dangerous region from the simulated data. This result shows that the dump bed lifting mechanism can stop efficiently upon reaching the dangerous region as indicated in Figure 10 where the error between the real experimental result and the simulated data is less than 1 degree. Finally, Figure 11 shows both the combination of real experimental results and simulated data.

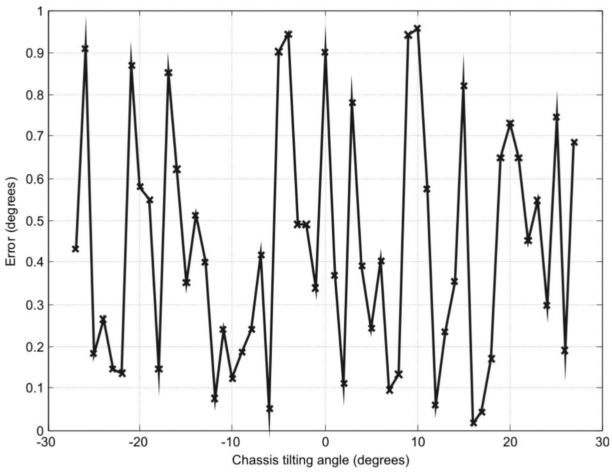

Figure 8: Errors between the experimental and simulated data for rising speed slow-down region of the dump bed.

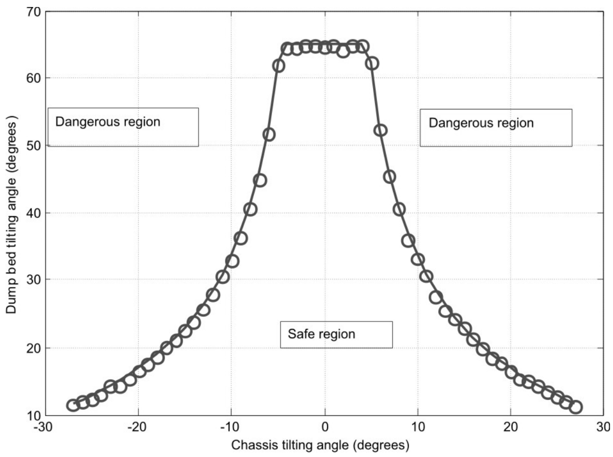

Figure 9: Points at which the dump bed stops rising.

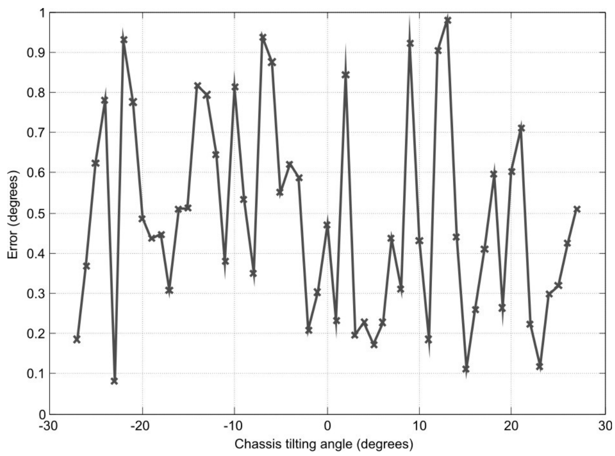

Figure 10: Error between the experimental and simulated data for region where the dump bed stops rising.

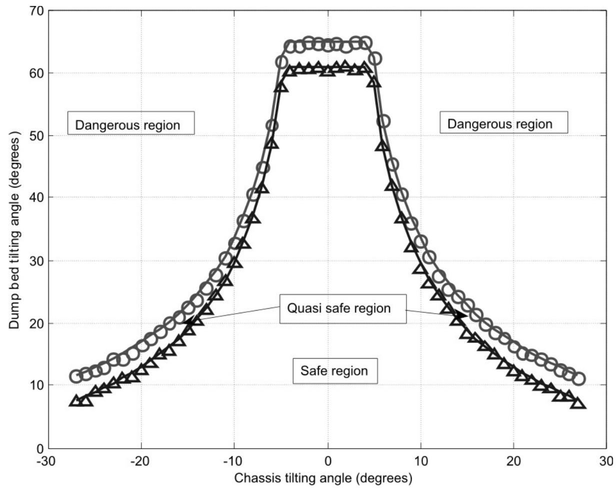

Figure 11: Final response plot for both simulated and experimental data for the region where the speed of the dump bed slows and the dump bed stops rising.

6 Conclusion

An intelligent dump truck tilt-over prevention system is proposed and successfully tested in this study. The system measures the tilt angle of the truck chassis and dump bed. The data are analyzed and used to control the speed of the lifting dump bed and the stopping angle so that the dump bed lifting range is within the safe region. The complete system developed in this project would have a significant effect on the safety of dump truck operators.

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