Stuck State Avoidance in Work Vehicle's Control with Hybrid Twin Framework

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Abstract This paper suggests an IoT device utilization for skid suppression for work vehicles in the framework of Hybrid Twin and the performances of IoT utilization are experimentally evaluated. In the autonomous driving of work vehicles, stuck state or lock state should be avoided because it is very difficult to escape from these states autonomously. First of all, a state transition diagram consisting of grip, skid, stuck and lock states is configured and a skid ratio is newly defined to measure the degree of skid. Then, a three-stage skid suppression method is suggested based on skid ratio and a controlling system is implemented by using MATLAB/Simulink. Using an actual snow blower, an IoT device with some filtering processes is incorporated and the three-stage skid suppression method is applied. The experimental results show that the suggested approach is feasible but not a three-stage but a two-stage skid suppression method is likely to be efficient because of insufficient noise reduction. As future work, the noise reduction should be improved and the skid suppression method should be implemented in a Hybrid Twin approach.

Keywords IoT, Skid, Sensor, Model Based Design, Digital Twin

1. Introduction

These days, such work vehicles as maintenance vehicles, bulldozers, grass cutters, and snow blowers are gradually being motorized. The electric system with motors is adequate for detailed control and it is strongly required that these work vehicles should be carrying autonomous driving function [1]. Different from passenger vehicles, the work vehicles must drive on wasteland, muddy ground, or ground covered with snow, etc. Here, the vehicle's power train should recover from a skid state automatically even if

it falls into such state, because the skid state may proceed to stuck or lock state if no control is executed.

Once a work vehicle is in these states, it is impossible to return to grip state by itself. As an example of snow blower, when it remains in a skid state, the snow under the crawler is dug out and the bottom of body touches the snow surface and as a result, the snow blower cannot move any more. This is defined a stuck state.

The detailed analysis on the mechanism of rubber crawler has already been reported [2] but this is on the inner structure of crawler and no discussions on skid, stuck and lock states are found. The modeling of hydraulic excavator with crawlers has been reported [3], but this is on the vibration analysis of crawler and body. In MathWorks, the anti-lock braking system is modeled dynamically [4] and the modeling of skid phenomenon is useful. However, here, the focus is just on the braking system.

This paper first configures the state transition diagram consisting of grip, skid, stuck, and locks states and analyzes the state transition conditions accurately. Next, a skid ratio newly defined by using the body speed and the drive-train speed to measure the degree of skid. The skid ratio is measured by using an IoT device attached to the work vehicle. Then, based on the skid ratio, a three-stage skid suppression method is suggested to carefully get the work vehicle back to grip state from skid state so as not to go into stuck or lock state.

The Model Based Design (MBD) method is indispensable for designing controllers in an automobile development [5] and in many other systems. The MBD method is already applied to the design of electric vehicles and attained efficient results [6, 7] and this method is applied to solve the problems dealt with in this paper. The MBD method is effective for only designing control systems and the Hybrid TwinTM [8] is developed for operating completed control systems dynamically and optimally. This paper suggests the utilization of acceleration sensor for detecting the skid state as an IoT

device which maps the driving state of work vehicle in the real system into the corresponding state as a Digital Twin. The obtained acceleration signal has much noise and three kinds of filters are applied for noise reduction. In the experiments with snow blower, the skid state is detected by estimating the skid ratio and not a three-stage but a two-stage skid suppression method based on the skid ratio is applied because of insufficient noise reduction. However, the two-stage skid suppression method itself would have a promising performance in the practical application.

In the followings, the problems dealt with in this paper are defined and the Hybrid Twin approach is described in Chapter 2. Chapter 3 is dedicated to the modeling of driving states of work vehicle in the Virtual Twin. The model of work vehicle's controller is implemented by MATLAB/Simulink and three-stage skid suppression method is shown in Chapter 4. Chapter 5 is assigned to the experimental results with a snow blower. Here, three kinds of filters for obtaining skid ratio from actual acceleration sensor signal are shown and two-stage skid suppression method is suggested. Finally, this paper is concluded in Chapter 6.

2. Work Vehicle Control and Hybrid Twin Framework

2.1. Problems in Work Vehicle's Control

The work vehicles with crawlers must drive on wasteland, muddy ground, or ground covered with snow, etc., and they often go into the skid state. The skid state and the stuck state are shown in Fig. 1 and the vehicle should recover from a skid state automatically when the vehicle drives autonomously. Because, the skid state may proceed to stuck state shown in Fig. 1 if no control is executed. In case of a snow blower, it is defined a stuck state that the bottom of the vehicle touches the snow surface just under the vehicle because the snow under the crawler is dug out if the crawler continues to rotate. Once a work vehicle is in stuck state, it is impossible to return to normal grip state by itself. Therefore, the problems are that firstly, the skid state should be detected and secondly, the work vehicle should be controlled to return to the grip state so as not to fall into stuck state.

Figure 1. Skid and stuck states of snow blower

2.2. Hybrid Twin Approach

Figure 2. Digital Twin, Virtual Twin and Hybrid Twin

A Hybrid TwinTM [8] consisting of Virtual Twin and Digital Twin is used to mainly control an on-line system optimally. This approach is the extension of Digital Twin [9] and a Virtual Twin is added for separating the models for simulation from Digital Twin as shown in Fig. 2. Here, the Digital Twin is the numerical representation of real system while the Virtual Twin is the modeling of the system. The set of parameters extracted in the Digital Twin by, for example, IoT devices, is the input to the Virtual Twin. The models in the Virtual Twin are executed and as a result, the controlling parameters are given back to the real system. The loop consisting of Digital Twin, Virtual Twin and optimization of real system is repeated with the specified time step. Therefore, the Digital and the Virtual Twins must be executed very fast and a technique to convert a 3-D simulator to the corresponding 1-D simulator is required. The Hybrid Twin approach has already been

applied to such mission-critical control systems as in wind-generation, nuclear power reactor or smart factories. In the followings, the Hybrid Twin approach is applied to solve the problems in work vehicle's control.

3. Modeling of Driving States of Work Vehicle in Virtual Twin

3.1. Driving State Definition by Crawler Speed and Body Speed

The driving states of work vehicle with crawlers are defined as “grip state”, “skid state”, “stuck state” and “lock state.” These states are modeled by using the body speed $V_b(t)$ and the crawler speed $V_c(t)$ as shown in Fig. 3. The driving load $F_l(t)$ also affects these speeds as well as the ground condition for work vehicles.

Figure 3. Body speed and crawler speed

As shown in Fig. 4, when $V_b = V_c$, here, the time parameter is omitted, the work vehicle is in a grip state. If V_c becomes larger than V_b , the work vehicle goes into skid state or in stuck state as mentioned in Fig. 1.

Figure 4. Work vehicle's driving states

The difference between skid and stuck states is the body speed V_b . In the stuck state, $V_b = 0$ as described with Fig. 1. In the lock state, the vehicle meets heavy load such as thick snow wall and the vehicle cannot move at all. The transitions among these states are shown in the state transition diagram shown in Fig. 5. Each of the states is defined by comparing V_b and V_c as shown in this figure. When the crawler speed V_c in the grip state is increasing or the body speed V_b is decreasing, the vehicle is going into the skid state. In order to get out of the skid state, V_c must be reduced or V_b should be increased. The skid state is the entrance to stuck state or lock state which must be avoided under the autonomous driving. Therefore, a controller to reduce the crawler speed V_c is necessary and this is the original idea as well as utilizing the skid ratio defined next.

Figure 5. State transition diagram

3.2. Skid Ratio Estimation

The skid ratio λ is defined by equation (1) by using V_c and V_b . Such a state with $\lambda = 0$, $\lambda \rightarrow 1$ or $\lambda = 1$ corresponds to grip state, skid state or stuck state, respectively, as shown in Fig. 5. The crawler speed V_c is obtained by such physical parameters on the ground as static frictional force, dynamic frictional force, rolling resistance force, resistive load as well as driving force given to the crawler itself [7]. On the other hand, the body speed V_b is not obtained analytically and in the previous approach [7], a dedicated wheel is used for directly measuring V_b . However, a dedicated wheel is not desirable because of its durability for a snow-covered ground or muddy ground, etc.

In case of passenger electric vehicle, Fujii and Fujimoto [10] suggested the usage of acceleration sensor for slip ratio (or skid ratio) control without any dedicated wheel. This method is likely to be applicable to the case of hybrid work vehicle with combustion engine although it has a large amount of noise and vibration. The equations for estimating slip ratio (or skid ratio) λ are shown below.

$$\lambda = \frac{V_c - V_b}{V_c}, \quad (1)$$

$$J_\omega \dot{\omega} = T - r F_l, \quad (2)$$

$$M \dot{V}_b = F_d - F_l, \quad (3)$$

$$V_c = r \omega, \quad (4)$$

$$\dot{\lambda} = -\frac{\dot{\omega}}{\omega} \lambda + \left(1 + \frac{J_\omega}{r^2 M}\right) \frac{\dot{\omega}}{\omega} - \frac{T}{r^2 M \omega} + \frac{T - \omega J_\omega (M a)}{r M \omega}. \quad (5)$$

Here, J_ω , ω , T , r , F_l , M , V_b , and F_d are inertia moment at rotating shaft of wheel, angular speed of motor, motor torque, wheel radius, driving load, vehicle weight, body speed and driving force, respectively. These physical parameters are shown in Fig. 6. Especially, only the parameter “ a ”, the acceleration of vehicle, is needed for estimating the skid ratio λ in equation (5). The estimated skid ratio $\hat{\lambda}$ is obtained by solving differential equation (5). The calculation of skid ratio $\hat{\lambda}$ corresponds to the 1-D simulator for skid state detection in Virtual Twin and the acceleration “ a ” is the output of Digital Twin.

Figure 6. Crawler's physical model

4. Modeling of Controller and Plant

4.1. Model Based Design Approach

The Model Based Design (MBD) method [5] is an indispensable tool for designing and developing complicated and highly reliable embedded controller, such as ECU's (Electronic Control Units) in automobiles. In this method, the co-simulator which simulates the whole vehicle is implemented by connecting models. The MBD method has some design phases consisting of controller (ECU) and plant in real and virtual spaces. The controller and the controlled objects (plants) are modeled into virtual space. The interactions between controller and plant in the virtual space are sufficiently simulated and the controller can be efficiently designed.

4.2. Modeling of High-Level Controller

The top view of snow blower model is shown in Fig. 7. This model can be extended to vehicles with crawlers. The snow blower model consists of high-level controller, power system, and drive system controller. The top view of plant

is a block named “Drive System Plant.” The details of plant model are found in [11], where the interactions between environments and crawlers are precisely described. Finally, the hardware and software co-design method is applied to partition the high-level controller into hardware (micro-processor) and software (embedded program).

In Fig. 7, the target speed $V_o(t)$, the crawler speed $V_c(t + \Delta t)$ in the next time step, the estimated skid ratio $\hat{\lambda}(t)$, the generated (necessary) torque $F_c(t + \Delta t)$ and the measured acceleration $a(t)$ are given to the high-level controller and it generates the next speed $V_s(t + \Delta t)$.

Figure 7. Top view of snow blower model

Figure 8. Skid suppression controller

The skid suppression controller shown in Fig. 8 is included in “Drive System Controller” block. The current crawler velocity of snow blower $V_c(t)$ and the estimated skid ratio $\hat{\lambda}(t)$ calculated by equation (5) from the acceleration $a(t)$ are inputs to this controller and the crawler speed in the next time step $V_c(t + \Delta t)$ is an output.

The parameters in Fig. 8 are shown in Table 1. Here, the skid suppression control is executed in three stages, however, any number of stages can be implemented. The actual values of parameters are shown in experimental results.

Table 1. Crawler Speed Reduction according to Skid Ratio

No.	Skid Ratio	Reduced Speed
1	$\hat{\lambda}(t) < s_1$	$V_c(t) = V_c(t + \Delta t) \times r_1$
2	$s_1 \leq \hat{\lambda}(t) \leq s_2$	$V_c(t) = V_c(t + \Delta t) \times r_2$
3	$s_2 < \hat{\lambda}(t)$	$V_c(t) = V_c(t + \Delta t) \times r_3$

Here, the parameters s_i ($i = 1, 2, \text{ and } 3$) are such ones to divide the skid ratio into three stages and r_i ($i = 1, 2, \text{ and } 3$) are reduction ratios of crawler speed. As described in section 3.1, it is necessary to reduce the crawler speed to avoid stuck or lock state and to go back to the grip state. The drive system controller corresponds to a Virtual Twin which generates the next crawler speed $V_c(t + \Delta t)$ from the output of Digital Twin as shown in Fig. 9. The MBD method is used for “designing” controller systems while the Hybrid Twin is used for “operating” the completed controller system dynamically.

Figure 9. Actual Hybrid Twin with drive system controller

5. Experimental Results

5.1. Snow Blower and Acceleration Sensor

	HSM1390i(JN)	Dimensions
	Length [mm]	1,690
	Width [mm]	920
	Height [mm]	1,340
	Weight [kg]	245

Figure 10. Snow blower used in experiments

The snow blower [12] taken as an example is shown in Fig. 10. This is the actual snow blower which can be obtained as a product.

As described in section 3.2, the skid ratio $\hat{\lambda}$ is estimated from the acceleration a by using equation (5). The acceleration sensor which is incorporated in the snow blower is shown in Fig. 11. This 6-axis gyro sensor, “InvenSense MPU-9250” [13], is cost effective and it can be connected to the ECU in the snow blower by way of CAN (Control Area Network). This sensor corresponds to the IoT device which extracts the numerical data (Digital Twin) from the real system as shown in Fig. 9.

	Specifications	Core Voltage	2.4V ~ 3.6V
		I/O Voltage	1.71V ~ Core Voltage
		Interface	I2C or SPI
		Size	13×11 mm
		Weight	0.45 g
	Acceleration	Range	±4 G
		Resolution	16 bit
		Output Rate	0.24 ~ 4,000 Hz
	Gyro	Range	±500 deg/s
		Resolution	16 bit
		Output Rate	4 ~ 8,000 Hz
	Cost	Unit	\$20

Figure 11. Specification of acceleration sensor

5.2. Filtering of Acceleration Sensor Signals

The filters for noise reduction of acceleration sensor signals are suggested and evaluated. Three kinds of filters are tested against the acceleration sensor signal obtained during driving on the flat asphalt floor. Here, two snow blowers are serially connected by a cable and the latter snow blower tows the former one to skid it as shown in Fig. 12.

Figure 12. Skid state generation by towing

The raw signal obtained from the acceleration sensor has much noise because of vibrations of auger and engine as shown in Fig. 13. Here, the typical band rejection filter removing the noises ranging from 1Hz to 1MHz is applied. Its transfer function is shown in equation (6).

$$H(s) = \frac{s^2 + \omega_1 \omega_2}{s^2 + (\omega_1 + \omega_2)s + \omega_1 \omega_2}, \quad (6)$$

where, $\omega_1 = 2\pi \times 1$ and $\omega_2 = 2\pi \times 10^6$.

Figure 13. Acceleration signal after band rejection filtering

Figure 14. Acceleration signal after band rejection filtering (magnified)

The acceleration signals obtained by sensor after applying the above band rejection filter and by the dedicated wheel, respectively, are shown in Fig.'s 13 and 14. In these figures, the horizontal axis and the vertical axis mean the time and acceleration, respectively. The actual dedicated wheel measuring the speed is shown in Fig. 15 and the acceleration signal calculated from this wheel is set as a goal.

Figure 15. Dedicated wheel for measuring speed

As shown in Fig. 14, the signal after applying the band rejection filter still has large oscillation. Then, the low pass filter shown by equation (7) is further applied.

$$H_c(z) = \frac{cz}{z+(c-1)}, \quad (7)$$

where, the cycle $T = 0.004$ [sec] and $c = 0.01$.

The result is shown in Fig. 16. The oscillation of signal obtained by the acceleration sensor is reduced and the signal's behavior is relatively the same as that obtained by dedicated wheel. However, from 0 to around 14 seconds when the snow blower is holding, the signal measured by acceleration sensor is not 0 while the signal obtained by dedicated wheel remains 0.

Figure 16. Acceleration signal obtained after low pass filter application

Then, the gravity component is tried to be removed from the signal because it is likely that the gravity component exerts some influence on the acceleration signal. The acceleration sensor has a clinometer and its measurement result can be used. The obtained signal is transformed by applying the filter shown by equations (8) and (9).

$$\hat{A}_x = A_x - g \sin \hat{\theta}, \quad (8)$$

$$\hat{\theta} = \tan^{-1} \frac{A_x}{\sqrt{A_y^2 + A_z^2}}, \quad (9)$$

where, $\hat{A}_x$, A_x , A_y , A_z , g , and θ are estimated x -axis acceleration, the value of acceleration sensor in x -axis direction, the value of acceleration sensor in y -axis direction, the value of acceleration sensor in z -axis direction, gravity acceleration and gradient angle, respectively. The filtered results are shown in Fig. 17, and the oscillation of acceleration signal obtained by the acceleration sensor (shown as "After Gravity Component Rejection") is smaller than that obtained by dedicated wheel when the acceleration range is magnified. The behaviors between these signals are relatively similar with maximally 0.2 [m/s²] error and removing the gravity component is effective for utilizing the acceleration signal from the sensor. On the other hand, the elimination of gravity component makes it difficult to obtain the precise acceleration value when the snow blower moves on the slope.

Figure 17. Acceleration signal after gravity component filtering

5.3. Evaluation of Skid Suppression Control

The skid state detection and its suppression control problems mentioned in section 2.1 are tried to solve by using the suggested method. The experiments shown in Table 2 are executed.

Table 2. Details of experiments

No.	Ground Condition	Driving State	Slope (degrees)	Maximum Speed (km/h)
1	Snowy	without Skid	4~8	3 (0.83m/sec)
2	Snowy	with Skid	4~8	3 (0.83m/sec)

In experiment No.1, the skid ratios obtained by acceleration sensor and dedicated wheel are shown in Fig. 18. The vertical axis is the skid ratio. In the comparison of estimated skid ratio with the one obtained by dedicated wheel, the suggested estimation method from the filtered acceleration sensor signal and equation (5) is seemed to be practical except in holding periods. In the holding period, the crawler speed V_c is 0 and the skid ratio λ cannot be defined, however, this exceptional process has not yet been implemented and the skid ratio is mistakenly 1.

Figure 18. Comparison of skid ratios between estimated and measured

Moreover, when the snow blower is accelerated from just after holding period, the estimated skid ratio from sensor does not coincide with that obtained by dedicated

wheel. This is because of the gravity component elimination and the acceleration or deceleration value cannot precisely obtain when the snow blower drives on a slope. This problem must be improved in future.

Next, in the experiment No.2, it is verified whether the estimated grip or skid state coincides with the one obtained by dedicated wheel. The result is shown in Fig. 19.

Figure 19. Comparison of skid and grip states

The driving states shown in the upper part of this figure mean the driving states of former snow blower and “Skid” state is generated when it is towed by the latter cable-connected snow blower in Fig. 12. The driving states shown in the lower part of this figure, such as “Grip-e” or “Skid-e” is the estimated ones by acceleration sensor based on the method described in section 5.2. The skid state, “Skid-e,” is determined when the estimated skid ratio is greater than the specified threshold 0.4. Then, it is shown that there are some differences among time intervals of grip or skid states between generated and estimated cases with the maximum difference of 2 seconds. In the time interval from 5 to 7 seconds, the estimated skid ratio from acceleration sensor is large and the driving state in this time period is mistakenly estimated as “Skid-e.” This may be from the same reason mentioned with respect to Fig. 18. In section 4.2, three-stage skid suppression is stated but here, two-stage skid suppression is seemed adequate because of the insufficient accuracy of skid ratio estimation. When the skid ratio accuracy is improved, three or more stage skid suppression may be implemented. The suggested two-stage skid suppression method is shown in Table 3.

Table 3. Two-stage skid suppression method

No.	Skid Ratio	Reduced Speed
1	$\lambda(t) \leq 0.4$	$V_c(t) = V_c(t + \Delta t)$
2	$0.4 < \lambda(t)$	$V_c(t) = V_c(t + \Delta t) \times 0.5$

The feedback path in the Hybrid Twin shown in Fig. 9 is scheduled to be evaluated in future. This is the verification whether the snow blower can go back to grip state within specified time interval when the two-stage skid suppression method applied.

6. Conclusions

An IoT device utilization method in the framework of Hybrid Twin for work vehicle's control is suggested. Four such driving states as grip, skid, stuck and lock are defined. In autonomous driving, such state as stuck or lock must be avoided because the work vehicle in such states cannot escape by itself. The skid state is the entrance to these states and the speed reduction of driving device in skid state is a solution to get the work vehicle in skid state back to grip state. The skid ratio for quantifying the degree of skidding and the speed of driving device (e.g., crawler) is reduced based on the skid ratio by using three-stage skid suppression method. The Hybrid Twin is constructed with the skid controller as a Virtual Twin and with the acceleration sensor as a Digital Twin. The filtered acceleration signal obtained from real system is an input to the Virtual Twin and the speed of driving device is given to the real system as the specified speed in the next time step. The experimental results show that not the three-stage but the two-stage skid suppression method is efficient because of the insufficient noise reduction. However, the two-stage skid suppression method itself would have a promising performance in practical applications. Actually, the number of stages in skid suppression method should be flexible according to the performance of IoT device. As future work, the noise reduction should be improved and the skid suppression method should be implemented in a Hybrid Twin approach.

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