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`Bikeinformatics`: A Sensing Infrastructure with Two-Wheel Vehicles and its Application for Intelligent Transportation Systems with Information Science and Technologies

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ABSTRACT

In this paper, we introduce a project to achieve a sensing infrastructure with motorcycles for developing intelligent transportation systems (ITS) for motorcycles. Collected data from the project can be used not only for traffic safety and effectiveness but also for analyzing motorcycle dynamics. Such data can be used for various purpose. We also introduce some application that utilize the data. Then, as a sensing system for a motorcycle, we propose a reasonable prototype that consists of low cost MEMS sensors, and we also propose a measurement method to correct the sensors' error by integrated the sensors' output. Through the experiment with a real motorcycle equipped with both precise measurement devices and the proposed system, we have confirmed that the accuracy of the proposed system is better than the original IMUs' output.

Keywords: motorcycle, kinematics measurement system, motorcycle dynamics, inertial measurement unit (IMU), global navigation satellite system (GNSS), integrated navigation system, ITS (intelligent transportation systems),

1 INTRODUCTION

In traffic accident, motorcycle rides are 5 times (2.5 times) more likely to be injured (killed) than car drivers in Japan, 2010 [1]. Some of the reasons are related to the following characteristics of motorcycles and less available ITS (intelligent transportation systems) for motorcycle safety: (1) body size: no cabin to protect riders; small body and less space for intelligent transportation systems'(ITS) devices of safety; (2) cost: costly ITS devices against the product pricing; (3) vehicle dynamics: complex vehicle motion dynamics; un-self-standing structure; the gravity center also depends on a rider.

Traditionally, it is difficult to investigate the dynamics of motorcycle because it is intricately interrelated with the dynamics of rider. A massive amount of gathered sensing data from a lot of riders with the proposed system can be used to distinguish the dynamics of a motorcycle from that of a rider. The impact of the riders to the measured data can be averaged, and the dynamics of a motorcycle might be derived after removing that of a rider. Conventional approaches in mechanics focus on measuring the motorcycle motion accurately with precious measurement devices [2]. The devices are expensive and it is hard to equip such devices for many riders to obtain their motion data in actual field (public roads).

We have been proposing an information-scientific approach, that uses low-cost devices for each vehicle, but the amount of collected data covers its accuracy, and senses targets every day and by every rider. In this approach, the sensed data is collected through the Internet and is refined into a motorcycle bigdata. We call the approach `Bikeinformatics`.

The number of annual productions of motorcycles is 60 million and this number is sufficient to build a mobile sensing infrastructure with motorcycles. When a mounted device on a motorcycle is not only used as its own ITS device but also used as a mobile sensing device for such public infrastructure, the cost will be regarded as considerably lower. Although some car-telematics-systems are in practical use as a mobile sensing system, a motorcycles-telematics-systems can be reasonable as another sensing system, especially in ASEAN countries, where are the major market of motorcycles. In this paper, we introduce some of applications of `Bikeinformatics`.

There are several issues to achieve the project, `Bikeinformatics`. The first issue is hardware: how to develop mounted sensing devices and the internet of the motorcycles. The second issue is a bigdata: how to make them have a significant structure by labeling raw data. The third issue is its application: how to use the bigdata to achieve a safer world for (motorcycle) users and to make the society better.

In this paper, we focus on the first issue and we propose a reasonable mounted sensing system for each motorcycle and an roll angle estimation method with the measured data by the system. The proposed sensing system consists of low cost MEMS IMUs (inertial measurement units) and a GNSS (global navigation satellite system) receiver that is used to improve its motion sensing accuracy and a known motorcycle-kinematics model [3]. Through the experiment with JSAE Motorcycle working group (WG), we have confirmed that the accuracy of the proposed device is better than the original IMUs. We also introduce one of application of the third issue.

2 BIKEINFORMATICS

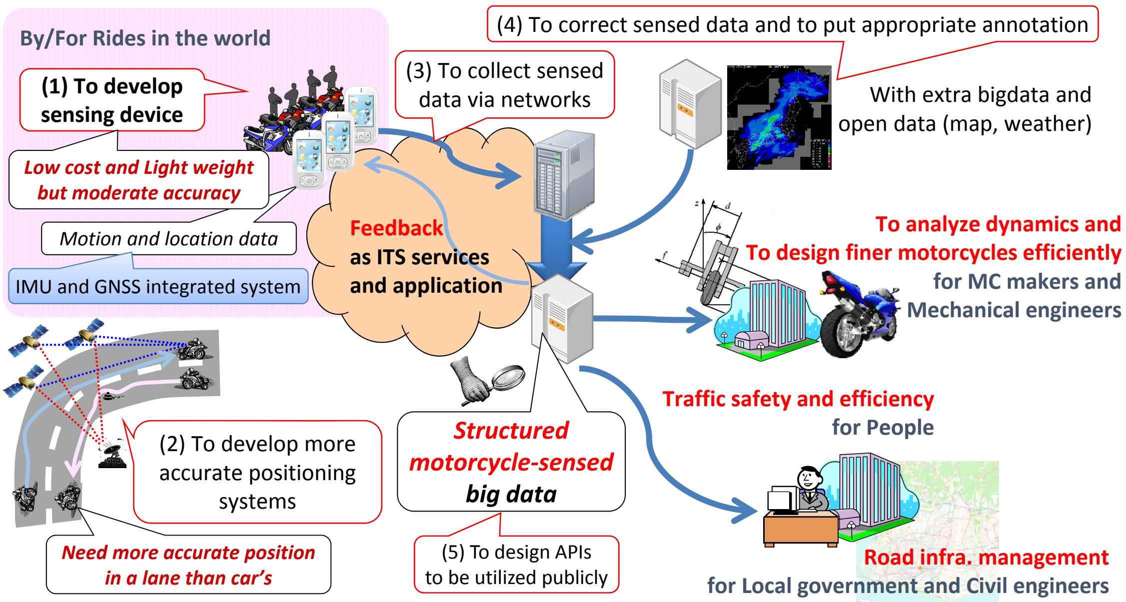


Figure 1. System Chart of Bikeinformatics

The purpose of Bikeinformatics (BKI) is to put a motion and location sensing device to all motorcycles in the world and to build bigdata of the riders, by the riders, not only for the riders as shown in Fig. 1. One of the motivations is to collect such data from a lot of motorcycles and riders in order to help mechanical engineers analyze motorcycle dynamics and to also help motorcycle manufacturers design finer motorcycles efficiently. Another is to use such data to help riders enjoy riding safely and conveniently. The other is to utilize such data socially. For example, it can be used to achieve traffic safety and efficiency for other people, and to manage road infrastructure for local government and civil engineers. Moreover, it can be used to improve traffic safety in mixed traffic with motorcycles and automated cars.

There are mainly five challenges. Firstly, how to develop low-cost and light-weight but moderate accuracy sensing device for a motorcycle. Secondly, due to the high mobility of motorcycle, it needs more accurate positioning system to utilize such mobility. Thirdly, how to collect sensed data via communication networks and how to store all sensing data around a motorcycle: a motorcycle's motion and a rider's motion by IMUs, trajectory by a GNSS receiver, and image and video by cameras. Fourthly, how to correct sensed data and to put appropriate annotation with external bigdata and open data, such as digital map and weather information because it is possible to associate weather information with motion sensing data by using time and location information of the sensed data. Lastly, how to design application programming interfaces (APIs) to be utilized publicly.

In this paper, we introduce a prototype of the sensing system. We have also developed a smartphone application to sense its motion with its embedded MEMS IMU so far. This application can be used as an alternative sensing device, but it has been often suspended by thermal runaway of the smartphone. Thus, in this paper, we are developing a reasonable dedicated sensing device for a motorcycle.

2.1 BKI Applications

To let Bikeinformatics be an infrastructure in the future, we have to consider how to utilize it socially as well as for riders and the motorcycle industry. Other than utilizing the BKI data for analyzing motorcycle dynamics, one of the most favorable application for all tax payer is the crack and rut survey for public road.

The cost to construct and manage road infrastructure has been getting large and it has become a big problem in the world. It is costly for a local government not only to construct new roads but also to survey the condition of existing roads. There are several related researches and services with cars [4]. The world bank has developed a simple index of the condition of a road section named IRI (international roughness index) and it can be measured by acceleration sensors [5]. Ministry of Internal Affairs and Communication, Japan conducted an experiment where they gathered the acceleration data and location data of 20,000km from public buses and taxis that equipped with sensors. As a result, the simplified road survey performs the same as the conventional road survey method with special vehicles at three of the seven indexes for road surface survey. However, the result shows the difference at the other four indexes.

A motorcycle has some advantage because a motorcycle can move horizontally on a road whereas a car moves almost along a road. To equip our sensing device on commercial motorcycles at local bank in Hamamatsu city, we can obtain the sensed data of the city every day. Bikeinformatics data contains such motion data with location data, and it may complement such data of cars. Especially in the developing countries, motorcycle is the main transportation and they would confront the problem when they need to construct and manage a lot of roads in the near future.

3 BKI MEASURING METHOD

For Bikeinformatics, we need to develop a reasonable measurement system in order to obtain vehicle-motion data from lots of riders and their motorcycles. We have developed a prototype of the motion sensing system in 2013 [6]. The system consists of a low-cost microcomputer and motion sensors, such as inertial measurement units (IMU) and a GPS/GNSS receiver. In this section, we introduce an improvement of the system and a method to estimate the roll angle of the attitude of a motorcycle by the improved system.

3.1 Components of Sensing System

Our sensing system consists of the following low-cost sensors: a microcomputer; four IMUs; a GNSS receiver; a microSD card. Their detail is shown in Table 1. The appearance of the proposed unit is shown in Fig. 2 and it weighs less than 500 grams.

Each of the four IMUs is attached to the following four parts of a motorcycle because each of the parts move differently: the handle above the front suspension; the fork bottom below the front suspension; the body above the rear suspension; the swing arm below the rear suspension as shown in Fig. 3. The system can sense 3-axis acceleration and 3-axis angular rate at up to 400Hz with the IMU. The system can also get location data (NMEA sentences) at up to 20Hz with the GNSS receiver. In this paper, we use 100Hz as the sampling rate of each IMU and 20Hz as the update rate of the location by a GNSS receiver.

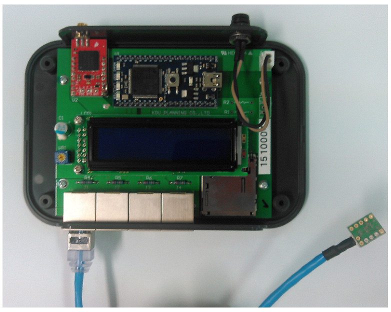


Figure 2. Appearance of the proposed sensing unit

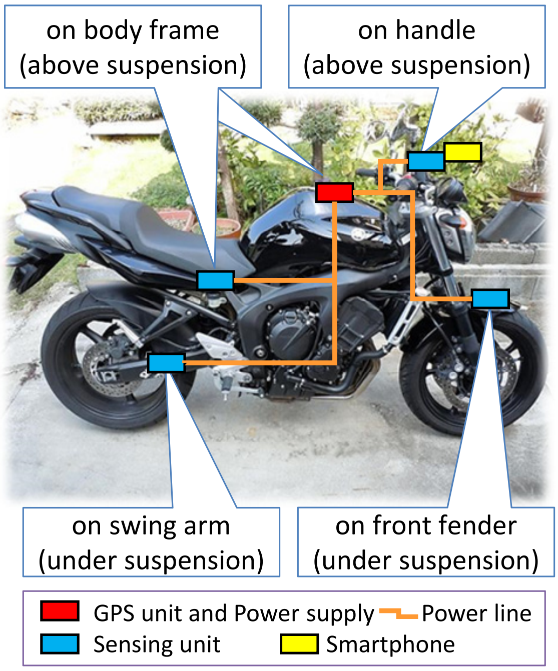


Figure 3. The sensing points of a motorcycle

Table 2 shows the measurement items that have to be measured in order to analyze the vehicle motion of motorcycles. The items with "Needed for analyzing Motorcycle's Dynamics" in the table should be measured according to [7]. JSAE Motorcycle WG has conducted an annual experiment

Table 1. Specification of Modules in Sensing Unit

component	name	spec	price
Micro-computer	mbed NXP LPC1768	32bit Cortex-M3 100MHz	7,000JPY
IMU	InvenSense MPU-9150	Acc:±16G, Gyro:±250deg/sec.	2,000JPY×4
GNSS receiver	Sparkfun Venus638	GPS, 20Hz, 2.5m CEP	6,000JPY
MicroSD card	–	SDHC UHS-I	1,000JPY

The total cost of a unit is 50,000JPY (around 500USD) including the assemble cost.

and they use the sensing systems that measures all the items in the table. In Bikeinformatics, we target to develop a sensing system that measures some of the fundamental measurement items. We select items based on how such items can be installed easily at low cost, and we confirm how the selected items work sufficiently. Since the other measurement items cannot be measured by the proposed system directly, we need to estimate them as the future work.

Table 2. Measurement Items for Motorcycle's Dynamics

Need for analyzing Motorcycle's Dynamics			
		JASE Motorcycle WG	
			Proposed System
Speed	✓	✓	✓(GNSS)
Roll Rate		✓	✓(IMU)
Roll Angle	✓	✓	calculable
Yaw Rate	✓	✓	✓(IMU)
Yaw Angles	✓	✓	calculable
Acceleration		✓	✓(IMU)
Steering Angle	✓	✓	N.E.M.
Steering Torque	✓	✓	N.E.M.
Slip-side Angle	✓	✓	N.E.M.
Trajectory		✓	✓(GNSS)
Cost	–	high	low
Weight	–	high	low

N.E.M. denotes that "need an estimation model."

3.1.1 Basic Evaluation of Sensing Unit

We evaluate the practical performance of the sensing system.

We have conducted a steady state circular test as the preliminary experiment with a real motorcycle equipped with both precise measurement devices by JSAE Motorcycle WG (its obtained value is referred as "WG" in the graph in the following figures) and the proposed sensing unit ("BKI"). The WG's devices are designed to measure data in order to analyze the vehicle dynamics of a motorcycle.

Figure 4 shows time variation of the biased error of the 3-axis gyroscope output (angular rate) of four IMUs, InvenSense MPU-9150, that are fixed to a desk in a room at 20–25 °C . According to the data sheet of the IMU[8], ZRO (Zero-Rate-Output) @ 25 °C is ±20dps (deg/sec) and ±0.24dps/ °C . Although each of the measured ZRO is smaller (±4dps) than the data sheet and almost stable as shown in the figure, these biased errors should be corrected at the attitude estimation.

Figure 5 shows the measured roll rate with the WG's sensing device and that of our system (BKI). As described above, the measured value of each axis by our system contains a biased error and its white noise is slightly bigger than that of the WG.

3.2 Roll Angle Estimation

We estimate the roll angle of a motorcycle to evaluate the accuracy of the proposed system. At the end of this subsection, we will compare the estimated roll angle by the following proposed methods to the measured roll angle by the WG's devices.

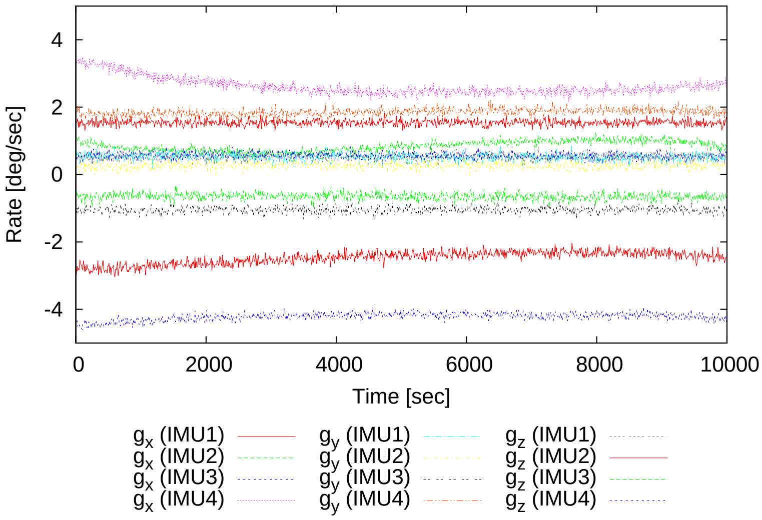


Figure 4. Time Variation of Biased Error of IMUs

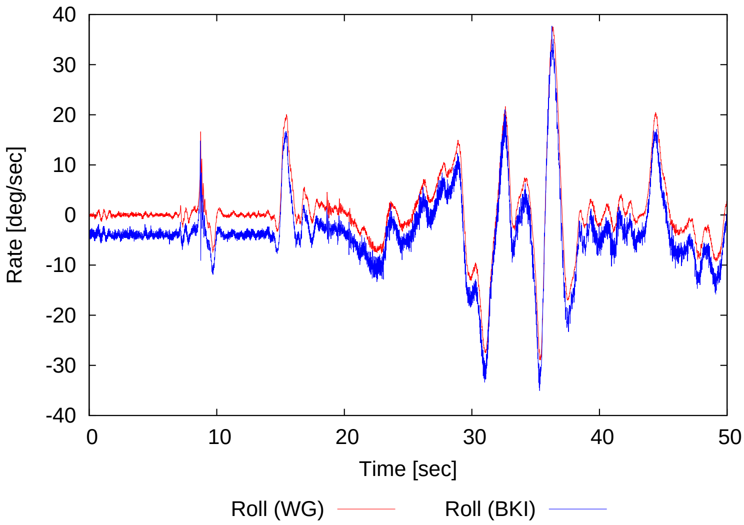


Figure 5. Comparing Measured Angular Rate g_x of Body

3.2.1 Coordinate Conversion

Since the IMUs are fixed to a motorcycle, the axes of the gyroscope output are affected by the attitude of the motorcycle and we need to rotate the axes of each IMU toward the same coordinate of the attitude.

Here, we give the following assumptions.

- *Ground coordinate* (x, y, z) denotes the original coordinate where x-axis denotes the direction of true north, y-axis denotes the direction of true east and z-axis denotes the vertical direction as shown in Fig. 6.
- *Navigation coordinate* (x_1, y_1, z_1) denotes the coordinate that is the same as the rotated ground coordinate by the moving direction angle ψ around z-axis as shown in the same figure. Originally, the yaw angle means the difference between the heading of a motorcycle

and its direction angle. In this paper, however, we assume that the yaw angle is 0 and the pitch angle is 0 too because of focusing on the estimation of the roll angle. In other words, the heading and direction angle is the same, and the yaw-rate affects the moving direction angle.

- *Body coordinate* (x_3, y_3, z_3) denotes the coordinate of the IMU fixed on the body of a motorcycle. It is the same as the rotated navigation coordinate by the roll angle ϕ around z_1-axis and by the pitch angle θ around x_2-axis as shown in Figs. 7 and 8.

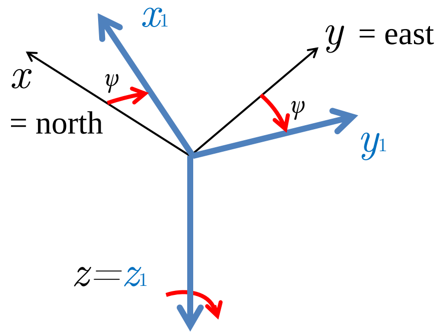


Figure 6. Direction angle of Motorcycle

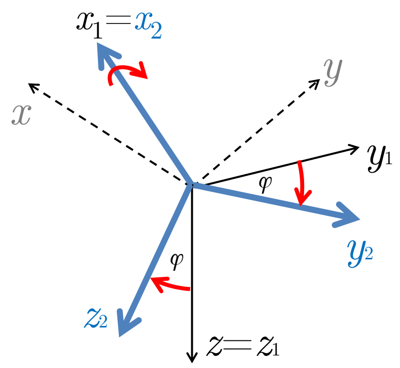


Figure 7. Roll angle of Motorcycle

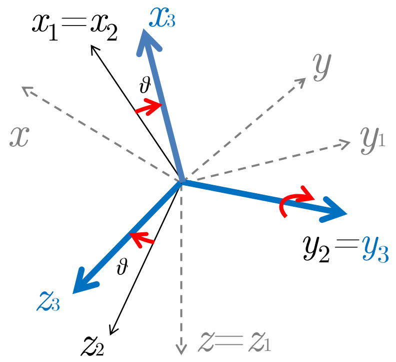


Figure 8. Pitch angle of Motorcycle

The axes of the attitude of a motorcycle is based on the navigation coordinate. Given the roll angle ϕ and the pitch angle θ as the attitude, the angular rate of the navigation coordinate (x_1, y_1, z_1) can be calculated by the following equation for the values of the body coordinated (x_3, y_3, z_3).

$$\begin{pmatrix} x_1 \\ y_1 \\ z_1 \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi & \cos\phi \end{pmatrix} \begin{pmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{pmatrix} \begin{pmatrix} x_3 \\ y_3 \\ z_3 \end{pmatrix}$$

Note that, hereafter, we do not consider the pitch angle due to the assumption above.

3.2.2 Two Approaches to estimate Attitude Angles

We consider the following two approaches for the attitude angle estimation. One is to accumulate the angular rate of each axis of the attitude with IMU output. The other is to use the relation of the gravity and the centrifugal force with both IMU output and GNSS output. The latter approach is known as *an integrated navigation system*.

Accumulation The angular rate can be measured by IMU output. Its response and variation can be good, but its biased error will be also accumulated and it will affect the estimated angle. It makes the attitude angle estimation difficult. Also, this attitude estimation does not work when the motorcycle is stationary.

Two forces The centrifugal force CF can be calculated as $CF = mr\dot{\psi}^2$ or $CF = v\dot{\psi}$ where m denotes the mass, r denotes the radius of turn, ψ denotes the direction angle and $\dot{\psi}$ denotes its temporal differentiation, and v denotes the forwarding speed. The forwarding speed v and the direction angle ψ can be measured by GNSS output.

When a motorcycle is stationary and leaned, the gravity force g is divided to y_3-axis and z_3-axis, denoted a_{y_3} and a_{z_3}, respectively, and the roll angle ϕ' can be derived as the following equation.

$$\phi' = \tan^{-1}\left(\frac{a_{y_3}}{a_{z_3}}\right)$$

When a motorcycle is running, it is forced not only by the gravity but also by the centrifugal force as shown in Fig. 9. Thus, in this case, the roll angle ϕ' can be derived as the following equation.

$$\phi' = \tan^{-1}\left(\frac{mr\dot{\psi}^2}{mg}\right) = \tan^{-1}\left(\frac{v\dot{\psi}}{g}\right) \tag{1}$$

The measurement results of the two forces contain no accumulated error, but the update rate of GNSS is slower than that of IMU, and the measurement error can be larger than the former approach.

Note that, in this paper, we do not consider the pitch angle due to the assumption above.

We use the sensor fusion, also known as the complemental filter, in order to correct the accumulated error of the former approach by the latter approach.

3.2.3 Two Types of Roll Angle

There are two roll angles: the dynamic-roll angle and the body-roll angle as shown in Figs. 9 and 10. The reason why the dynamic-roll angle is distinguished from the body-roll angle is that the gravity and the centrifugal force are related to both the mass of the motorcycle and the rider whereas the body-roll angle is only related to the motorcycle. Since the IMU is attached to the body of a motorcycle, the divided force of the gravity and the centrifugal force can appear on the y_3-axis as shown in Fig. 10. It is necessary to consider the remaining acceleration a_{y_3} in order to derive the body roll angle ϕ. The body roll angle ϕ can be derived as the following equation.

$$\phi = \tan^{-1}\left(\frac{v\dot{\psi}}{g}\right) - \sin^{-1}\left(\frac{a_{y_3}}{\sqrt{(v\dot{\psi})^2 + g^2}}\right) \tag{2}$$

Hereafter, ϕ denotes the body roll angle and ϕ' denotes the dynamic roll angle. The roll angle of the former approach means the body roll angle.

3.2.4 Sensor Fusion / Complemental Filter for Attitude Estimation

We adopt the sensor fusion, also known as the complemental filter, to combine the two approaches. Given a coefficient α, the estimated body roll angle ϕ is derived as the following equation.

$$\phi = \alpha\left(\hat{\phi} \text{ by the gravity and CF}\right) + (1-\alpha)\left(\hat{\phi} \text{ by the accumulated Roll rate}\right)$$

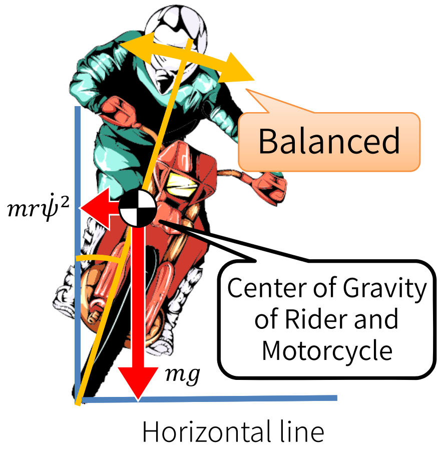


Figure 9. Dynamic roll angle of Motorcycle and Rider

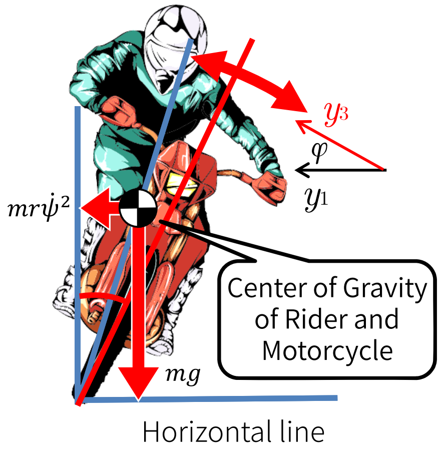


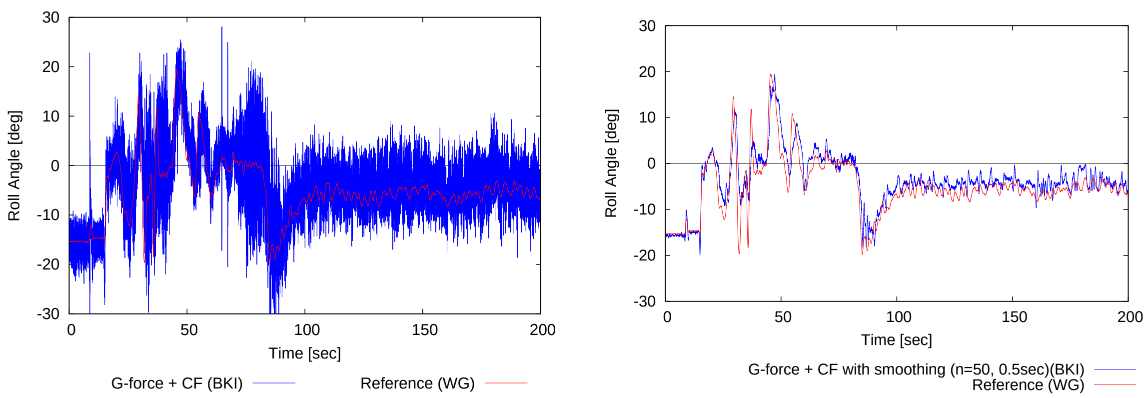
Figure 10. Body roll angle of Motorcycle

3.2.5 Evaluation of Estimation

Before the evaluation, we have simply removed the biased error by subtracting a certain value, the average of measured biased error, to each axis of the gyroscope output. We have also simply complemented the lack of measured values such as the forwarding speed and direction angle because the update rate of GNSS is 20Hz whereas that of IMU is 100Hz.

The data used in this evaluation is from the preliminary experiment of a steady state circular test as mentioned above. In the experiment, the motorcycle was stationary with its side stand ($\psi = -15.1$[deg]) for first 15 seconds, the rider rode it and then conducted a formation lap from 15 to 85 sec., and conducted a steady state circular test after 85 sec.

Figure 11 shows a result of the estimated roll angle by the former approach that uses the gravity and the centrifugal force. As shown in the figure, the estimated angle is roughly same as the reference angle by the measurement device of JSAE Motorcycle WG. However, the values are too sensitive and contain much noise. The smoothed result in Fig. 11 (b) is derived as the moving average of $[t - 0.25, t + 0.25]$ (sec.), and this smoothing process does not make the result delay. However, the estimated result is behind by about one second from the reference (WG) when the angle changes widely. Also, the response of the estimated angle is not able to follow such changes sensitively.



(a) Raw Estimated Roll Angle

(b) Estimated Roll Angle after Smoothing

Figure 11. Estimated Roll Angle by Gravity and Centrifugal Force

Figure 12 shows a result of the estimated roll angle by accumulating the roll angle rate converted to the navigation coordinate. As shown in the figure, the response of the estimated angle is good, but the estimation error is accumulated as time progresses. The reason why the estimation result looks good for the first 15 seconds is that the motorcycle is stationary with its side stand and the measurement noise caused by vibration from its engine and the road was small. After a lapse of the 15 seconds, the measurement result can contain more noise by such vibration, and it will be accumulated.

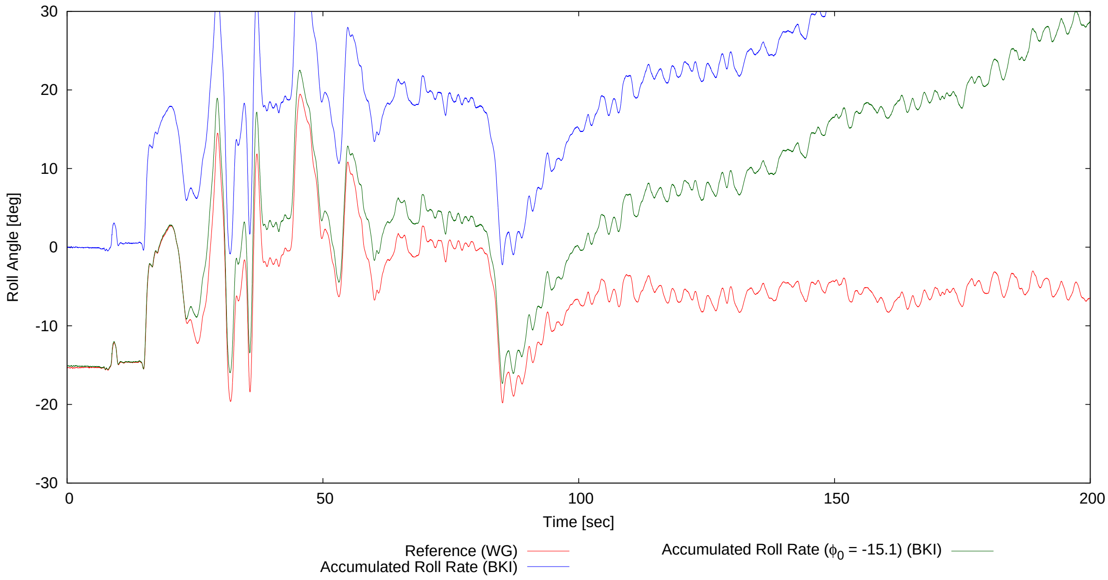


Figure 12. Estimated Roll Angle by Accumulated Roll Rate

Figure 13 shows the results of the estimated roll angle by the sensor fusion of the two approaches with the several kinds of the coefficient α from 0 (the accumulated angle rate) to 1 (the two forces). The larger $alpha$, the better response. The smaller α, the better accuracy. As shown in the figure, $\alpha = 0.01$ or near value can be reasonable.

3.2.6 Discussion

In this paper, we have not adopted any noise reduction methods and filters, expect the biased error offset. We have also not considered the yaw-angle and the pitch angle in the calculations of this paper. Some improvements are needed as future work.

According to Figs. 9 and 10 and Eqns. (1) and (2), the difference of the dynamic roll angle and the body roll angle can be derived. Therefore, it could be possible to estimate the riding position of the rider on a motorcycle. This estimation will be future work.

4 CONCLUSIONS

In this paper, we have outlined the concept of Bikeinformatics and a few of its applications. As a prototype of a reasonable sensing device for Bikeinformatics, we have proposed low-cost and moderate-accuracy sensing system for a motorcycle, and we have evaluated a roll angle estimation method for the system. As future work, we improve the accuracy of the sensing system, and we develop a data collection system and database system of Bikeinformatics data.

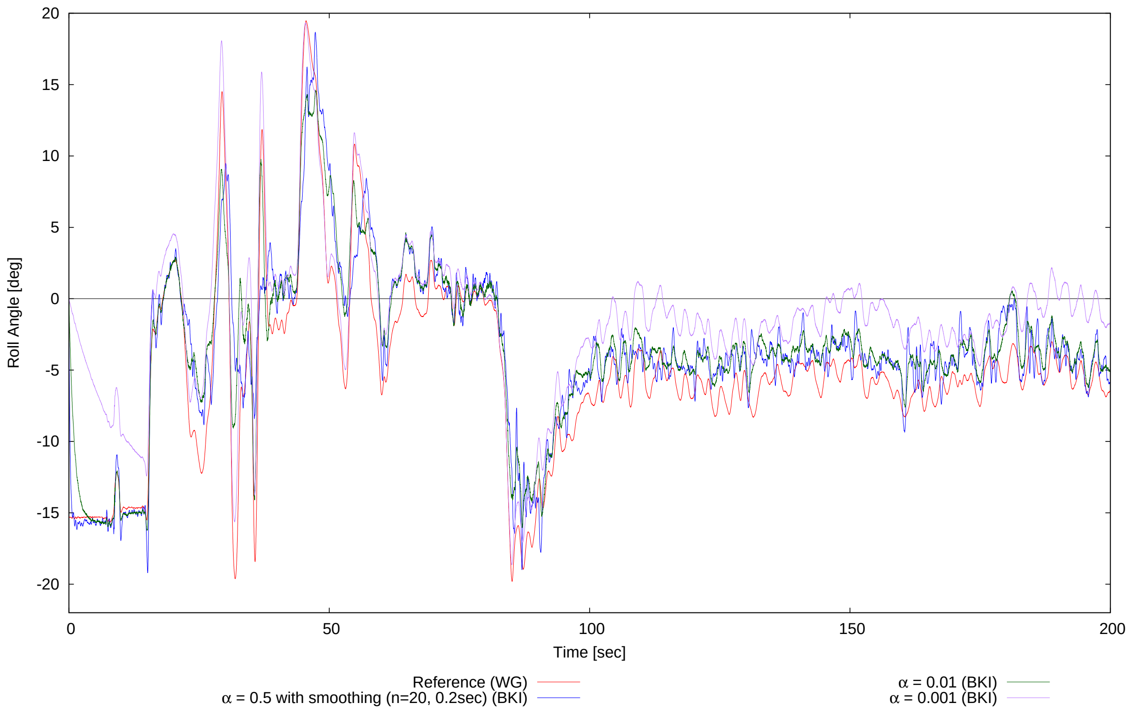


Figure 13. Estimated Roll Angle by Sensor Fusion

Acknowledgments

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