Modeling and Performance Evaluation of 6-Axis Robot Attitude Sensor

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***Abstract*—We propose a method for modeling a 6-axis robot attitude sensor which measures the orientation of the robot platform on which the sensor is installed. We avoid the technical difficulty in applying the unit step input for analyzing the sensor output in the time domain by employing a simple ramp input. We can still obtain a step response from the ramp input and moreover, provide an easy way of identifying the system transfer function of the robot attitude sensor. Based on the proposed method, we can accurately characterize the robot attitude sensor and provide a solution to reshape its output to meet any field requirements, such as those from 3D robot mapping, autonomous navigation, and robot motion control in the outdoor environment. We demonstrate the feasibility of the proposed method using the experimental result obtained by applying a ramp input to a sophisticated motion control device on which the robot attitude sensor prototype is installed.**

***Index Terms*—robot attitude sensor, 3D robot mapping, robot motion control, transfer function**

I. Introduction

The pose of a rigid body in the three-dimensional (3D) space is represented by its position and orientation with reference to a fixed coordinate system. In the Euclidean coordinate system, a 3-element vector consisting of x, y, and z coordinates represent the position of the rigid body. The orientation is simply angular displacement (or amount of rotation) with respect to a fixed coordinate axis. Accuracy and low latency of the measured orientation is important for robot applications, including the Simultaneous Localization And Mapping (SLAM) and robot motion control in the field operation scenarios.

A robot attitude sensor (in what follows, it will be referred to as "RAS" for short) in the present study refers to a sensor which measures the orientation of a robotic platform on which the RAS is installed. For a robot operating in the outdoor field, the orientation information is very important to quickly compensate for the position error due to unexpected hump or slope commonly found in the irregular terrain. Fig. 1 illustrates a typical roll motion experienced by an autonomous robot driving in the irregular (sloped) terrain.

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The importance of accurate orientation information of a robot platform is rapidly increasing along with the fast advances of 3D sensors such as LiDAR or 3D camera with an immediate application to 3D robot mapping. In a typical example of 3D SLAM technique, LIO-SAM [1], which utilizes the attitude measurements of RAS, the orientation measurements are used to estimate the current motion of the robot and improves the 3D mapping quality compared to its predecessor, LOAM [2]. In this scenario, an abrupt change of orientation data due to unexpected hump or slope of the terrain readily leads to unreliable feature matching and subsequently wrongly computed motion estimates. A quick and practical solution to this unexpected orientation change is to simply discard the corresponding orientation data or suppress them through a relevant filtering process. In this regard, a fundamental requirement on the RAS may be no overshoot to an input step signal and low signal latency.

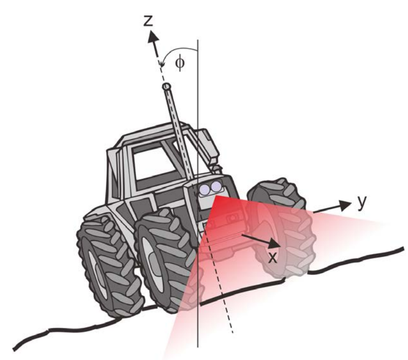

Fig. 1. A typical roll motion observed by an autonomous robot platform due to terrain undulations in the outdoor environment.

In evaluating the performance of the RAS, characterization of the sensor's performance in terms of step response (overshoot behavior and rise time) can be easily carried out if we can provide a step input to the robot platform on which the RAS is installed [3]. However, developing an ideal step input is impractical, and moreover, step inputs may cause mechanical overload to the robot platform or an apparatus for evaluating the RAS performance. In the work of [3], the input is in fact a trapezoidal signal imitating the ideal step signal; therefore, it may not be easy to apply the well-established time-domain analysis techniques related to unit step response. [4]. Therefore, in the work of [3], only the apparent output signals are recorded to determine the magnitude of overshoot and the rise time.

In this study, we propose a simple performance evaluation technique that utilizes a ramp input to avoid using the difficulty of developing an ideal step input. However, we could obtain the ideal unit step response from the ramp input by adopting a differentiation stage followed by a low pass filtering step to suppress undesired high-frequency noise due to the differentiation. The proposed method effectively provides a unit step response, and thus gives us a path to multitude of well-established control theories to determine the transfer function of RAS and apply signal shaping to satisfy the requirements laid by a specific robot task, such as 3D mapping, remote control [5], or autonomous navigation in the field.

The paper is organized as follows. Section II describes the proposed method for modeling the RAS using a ramp input which replaces the impractical unit step input. Also, a system identification procedure for estimating the transfer function of the RAS will be described. Section III describes an experimental result obtained by applying the proposed modeling method to the RAS prototype. Section IV concludes the paper and describes our future works related to the application of the RAS prototype.

II. The Proposed Method for Modeling Robot Attitude Sensor Using Ramp Input

The proposed method for modeling a RAS is based on the observation that the step input is obtained by differentiating a ramp input with an appropriate scaling.

$$r(t) = u_s(t) \leftrightarrow r(t) = tu_s(t) \tag{1}$$

$$R(s) = \frac{1}{s} \leftrightarrow R(s) = \frac{1}{s^2} \tag{2}$$

In (1)-(2), $u_s(t)$ and $tu_s(t)$ represent the unit step and ramp inputs, respectively, and $R(s)$ represents the corresponding Laplace transform.

In theory, a desired step response can be obtained by differentiating the output obtained from application of a ramp input. In practice, however, a significant high frequency noise may be introduced during the differentiation step. To suppress the distortion due to the high-frequency noise, we apply a low-pass filtering step subsequent to the differentiation step. If we allow a relatively large frequency band of 40 Hz, a resultant combination of the differentiation and the subsequent low-pass filtering may be obtained as follows.

$$G(s) = \frac{(80\pi)^2 s}{s^2 + 80\sqrt{2}\pi s + (80\pi)^2} \tag{3}$$

Fig. 2 shows a step response obtained by applying a ramp input to the robot platform and applying the combined filtering process of (3) to the RAS output.

The next step is system identification using the obtained step response and the ideal step input. For system identification, we used a commercial system identification function provided by System Identification toolbox of MATLAB. We used `iddata` function for this purpose. An ideal step input is prepared with an arbitrary duration of 0s followed by 1s. The sampling time is set to be identical to the data acquisition interval for digitizing the RAS output. The system identification is continued until the error between the estimated transfer function and the actual RAS output becomes less than 1%.

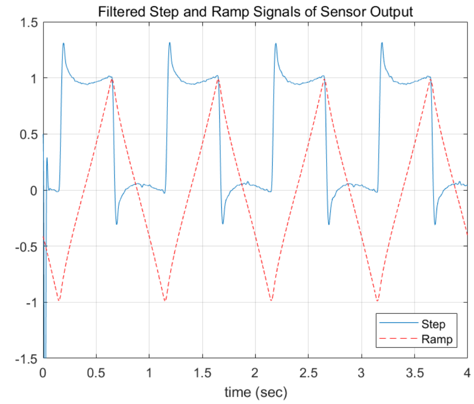

Fig. 2. A step response (blue solid line) obtained by applying a ramp input (red dotted line) with a subsequent step of differentiation and low-pass filtering.

The final step is to design a signal reshaping function for the obtained RAS transfer function. This step is required since task requirements may vary depending on a given task or operation scenario. For example, remote or autonomous driving of a field robot (including agricultural machines) may require zero-overshoot from a unit step input and zero-time delay of the step response. The amount of overshoot and time delay may effectively represent the performance of the RAS prototype.

In some cases, fast tracking performance may be one of high priorities, which inevitably causes some amount of overshoot to be introduced to the RAS output. In this sense, the final step is highly dependent on the given task requirements and operating scenario; for the present study, we choose the zero-overshoot and zero time-delay as the primary requirements on the RAS, which are reasonable requirements considering the low speed of task operation, including the 3D mapping and motion control of a robot in the outdoor environment.

III. Experimental Results

The developed RAS prototype is a MEMS-based 6-axis attitude sensor composed of 3-axis gyroscopes and 3-axis accelerometers. Since the attitude of a robot platform is directly measured by the roll and pitch angles, yaw angle is not considered in the present study (which is only related to the driving direction for a field robot operating in the 3D terrain). The RAS sensor outputs an analog signal along the x and y axis. Fig. 3 shows an experimental setup for modeling the transfer function of the developed RAS.

The motion generator is H-811.S2 6-axis motion hexapod, which can generate a precise movement of ± 17 mm, ±

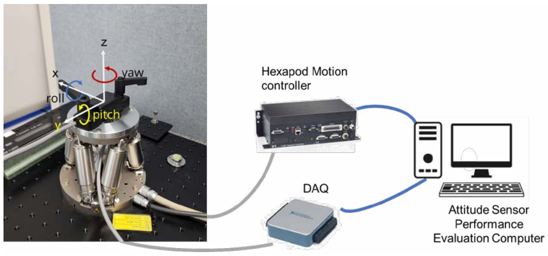

Fig. 3. An experimental setup for determining the transfer function of the developed RAS.

16 mm, and ± 6.5 mm and rotation of ±10°, ±10°, and ±21° along the x, y, and z axis, respectively. A ramp signal in the range of ± 2.5 V is generated and applied to the hexapod through the dedicated motion controller. The RAS output is captured and digitized by the DAQ device and fed to the computer for further filtering and evaluation of the RAS performance. Through the system identification step described in Section II, we obtained a transfer function as shown in (4).

$$G(s) = \frac{2.2835 \times 10^6 (s^2 + 7.325s + 32.37)}{(s + 182.7)(s^2 + 10.34s + 37.48)(s^2 + 111.6s + 9879)} \tag{4}$$

To design a filter that reshapes the RAS output and returns a signal that satisfies the task requirements, we constructed a Bode diagram (see Fig. 4) from (4) and designed a filter which compensates any undesired behavior in the frequency domain. In our case, a resonance was observed around 10 Hz, which has turned out to contribute to the occurrence of overshoot in the RAS output before the signal reshaping, and double poles and zeros were observed around 0.9744 Hz. We have designed a low pass filter effective around 10 Hz and based on the transfer function of (4), applied an inverse function to compensate for the double poles and zeros. The final RAS output is shown in Fig. 5. As shown in Fig. 5, the proposed RAS sensor outputs a signal without the overshoot and a time delay of about 50 ms, which is acceptable for a broad range of field tasks.

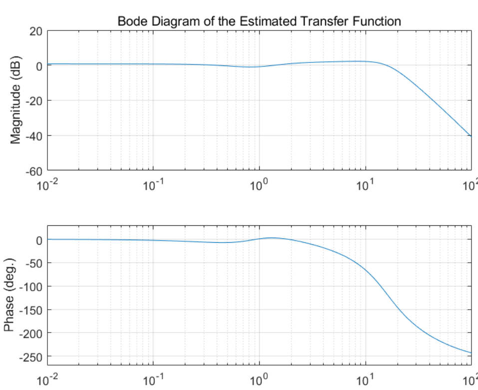

Fig. 4. The Bode diagram obtained from the estimated transfer function of the proposed RAS.

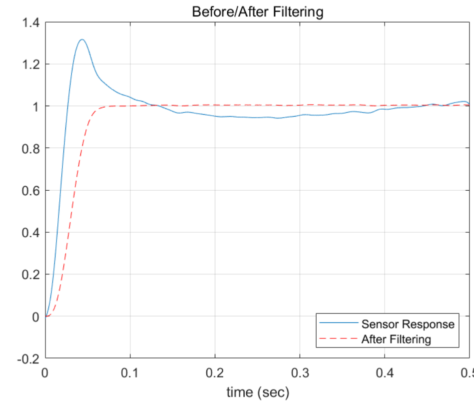

Fig. 5. The RAS output from the ramp input (blue solid line) and the RAS output after the proposed filtering is applied (red dotted line).

IV. Conclusion and Further Works

In this study, we proposed a method for modeling a RAS based on a ramp input. The proposed method effectively imitates the unit step response and therefore may readily utilize the well-established control theories for analysis and design of the RAS signal. Also, we described that the proposed method can be combined with system identification and filtering steps to effectively design a compensation filter to satisfy the field requirements, including the 3D robot mapping, autonomous navigation, and motion control in the outdoor environment.

One of our future works is to apply the proposed RAS to 3D robot mapping and show the effectiveness of the developed RAS to implement the state-of-the-art SLAM algorithms with a considerably reduced cost but high performance. Another task is to improve the current RAS interface to accommodate the Robot Operating System (ROS) ecosystem. To this purpose, we're currently updating the RAS with a digital interface including the USB-C and CANOpen interface and implementing ROS-based embedded control software.

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