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Impact of Tire Shape on Localization Accuracy in Piping Inspection Robots

Hirofumi Maeda

Abstract*: The sewerage pipes laid in Japan are extensive, spanning approximately 470,000 km, with most of them constructed during the high economic growth period from around 1955 to around 1973. According to indicators from the Ministry of Land, Infrastructure, Transport, and Tourism, the service life of sewerage pipes is estimated at 50 years. This suggests that many sewer pipes across Japan, installed over 50 years ago, are becoming obsolete. Consequently, piping inspections using robots have commenced in Japan. Currently, stand-alone types that can be inspected by a single robot are garnering attention. Meanwhile, we have been conducting research and development with the aim of implementing a small, easily portable, stand-alone piping inspection robot. Furthermore, numerous stand-alone types have been employed to prevent falls by adjusting the tire shape or the distance between the axles. However, this hardware approach does not completely prevent falls. Therefore, we have opted for a software approach to explore measures to prevent falls by controlling driving, aiming to achieve the advanced localization required for this purpose. We are currently in the stage of verifying the localization. However, accurately measuring the robot's position and orientation using general measuring instruments is challenging due to the curved piping. Hence, we developed a specialized three-dimensional position-measuring instrument for piping inspection robots. In this paper, we utilize the instrument to examine the influence of tire shape on localization. Additionally, we demonstrate the effectiveness of the localization method in an environment where tire shape does not affect the outcome.

***Keywords*: Localization, Tire Shape, Estimation Error, Inspection Robot, Water Pipe**

I. INTRODUCTION

Sewer pipes laid in Japan are vast, spanning approximately 470,000 km, with most constructed during the high economic growth period from around 1955 to 1973. Indicators from the Ministry of Land, Infrastructure, Transport, and Tourism suggest that the service life of sewer pipes is 50 years. This indicates that many sewer pipes across Japan, installed for over 50 years, are becoming obsolete. In fact, problems such as sewage pipes collapsing and rainwater gushing out due to frequent heavy rainfall. While replacing old pipes is desirable to address these challenges, it remains impractical due to cost and human resource constraints. Therefore, each local governments conduct detailed inspections to identify problem areas and conduct partial repairs on site. Nonetheless, these tasks are labor-intensive and time-consuming.

Given this background, piping inspections using robots have been introduced in Japan [1]. Currently, mainstream pipe inspection robots are remotely controlled from within an operation vehicle called a transport vehicle installed on the ground. This design allows for equipping the transport vehicle with essential functions such as power supply and a control unit, making the self-propelled robot lightweight and highly maneuverable. Furthermore, real-time control and monitoring are facilitated as the operator can remotely operate the system from the transport vehicle. However, the installation of a transport vehicle poses challenges such as space requirements and traffic regulation at the work site, leading to increased costs. Consequently, stand-alone types, capable of inspection by a single robot, are gaining attention. Nevertheless, the development of stand-alone piping inspection robots in Japan has been limited. Additionally, many overseas robots are designed for pipe diameters of 200 mm or more, rendering them unsuitable for Japan where numerous pipes have diameters of 150 mm [2]-[4][21]. In light of this, our research and development efforts focus on implementing a small, easily portable, stand-alone piping inspection robot. [5]-[9][22][23]. Therefore, achieving a stand-alone type pipe inspection robot requires ensuring the robot body's stability within the pipe. To address this, many stand-alone types have attempted to prevent falls by adjusting tire shape or axle distances. However, this hardware-centric approach does not offer complete fall prevention. Thus, we have opted for a software approach to mitigate falls by controlling driving, aiming to achieve the advanced localization necessary for this purpose [10], [11].

Currently, we are in the stage of verifying this localization method. However, accurately measuring the robot's position and orientation using conventional instruments is challenging due to the curved nature of piping. Hence, we developed a specialized three-dimensional position-measuring instrument for piping inspection robots. [12]-[20][24][25]. In this paper, we employ this instrument to assess the impact of tire shape on localization accuracy. Furthermore, we demonstrate the effectiveness of the localization method in scenarios where tire shape variation is irrelevant.

II. ROBOT LOCALIZATION METHOD

The localization method is performed under the following two conditions, similar to reference [11].

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A.3 Or More Tires Touch the Ground

The localization method assumes a robot consisting of four tires as shown in Figure 1, and three tires touch the inside of the pipe when stationary. However, if the robot is oriented directly along the direction of travel, all four tires will make contact. Note that the robot may vibrate based on the two diagonal tires that are in contact with the pipe when a shock is applied to the robot, and in this case, the robot will be in contact with the ground at two points momentarily. However, this phenomenon is not considered because it is rare and the robot immediately tilts toward the center of gravity and the vibration subsides.

B. The Bottom of the Tire touches the Inside of the Pipe

For all tires, the point where they touch the inside of the pipe is the area directly beneath them, perpendicular to the robot's top plate, and passing through the tire axle.

Fig. 1: Target Piping Inspection Robot

The coordinate system is a right-handed orthogonal coordinate system. In addition, as shown in Figure 2, we establish a robot coordinate system with the center of the robot as the origin, the front of the robot as the positive direction of the x-axis, and the direction directly beneath the robot's top plate as the negative direction of the y-axis. Furthermore, the pipe is positioned along the x-axis so that its center intersects with the origin of the absolute coordinate system. The pipe coordinate system is then inclined at an angle of θ_s [rad] with respect to the x-axis. Consequently, the piping coordinate system undergoes a rotation of θ_s [rad] around the y-axis relative to the absolute coordinate system. Note that the localization method is omitted here because the method in Reference [11] is used as is.

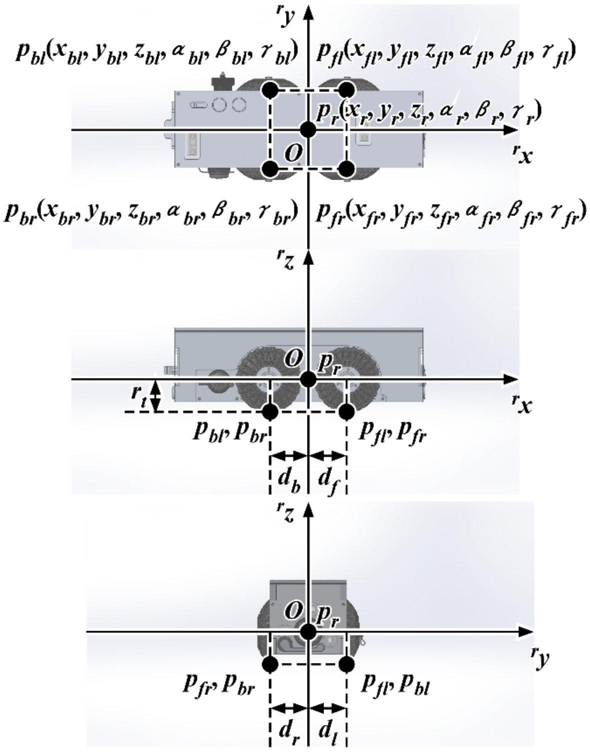

Fig. 2: Robot Coordinate System and Variable Declaration

III. EXPERIMENTAL EQUIPMENT USED FOR VERIFICATION

In order to assess the impact of the robot's tire configuration on localization accuracy, we will employ a specially designed three-dimensional position-measuring device. Furthermore, we have developed a novel verification apparatus capable of dynamically altering tire shapes. A brief description of each is provided below.

A. Contact Type Three-Dimensional Position-Measuring Instrument

The objective of the measuring instrument is to track the motion of a robot within a pipe. As shown in Figure 3, it is utilized by suspending it directly above a test area where the pipe is halved.

Fig. 3: How to Install the Measuring Instrument

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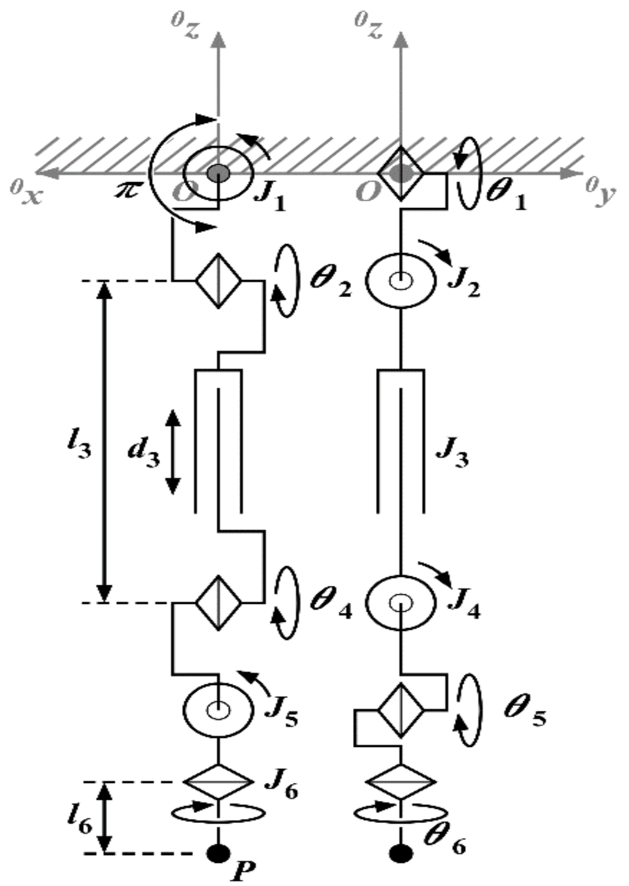
Furthermore, as illustrated in Figure 4, the measuring instrument features a six-degree-of-freedom linkage structure, with an encoder affixed to each joint. To ensure precision verification and calibration of the measuring instrument, a 6-axis stage is positioned directly beneath it, as depicted in Figure 5. This setup is depicted in Figure 6. The features of the measuring instrument and details of the control unit are described in references [18] to [20].



J_1-J_6	: the position of each joint
P	: the position of the end effector
$\theta_1, \theta_2, \theta_4$- θ_6	: θ_1 to θ_6 excluding θ_3 each indicates the rotation angles for J_1 to J_6 excluding J_3 [rad]
d_3	: d_3 indicates the displacement for J_3 [m]
l_3	: l_3 indicates the initial link length for J_3 [m]
l_6	: link length of the end effector [m]

※ The joint pair of J_1 and J_2 shares the same axis, so do the another joint pair of J_4, J_5 and J_6, which leads to there is no link length between each joint pair.

Fig. 4: Link Structure of Measuring Instrument

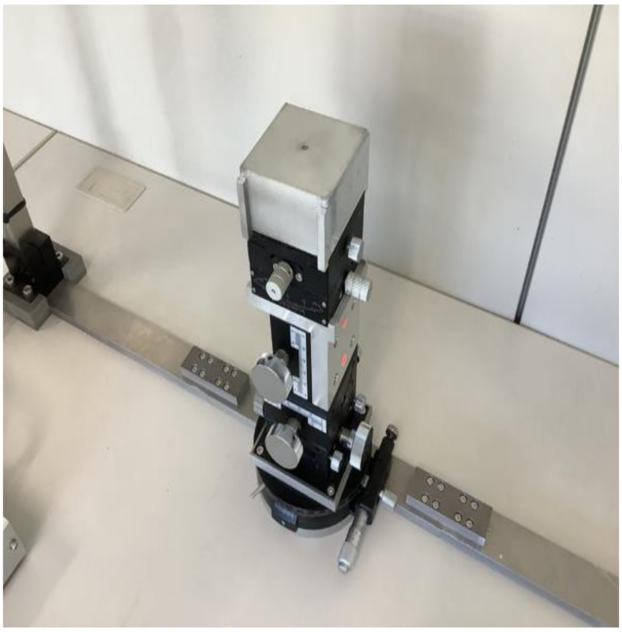


Fig. 5: 6-Axis Stage for Accuracy Verification and Calibration

Fig. 6: Measuring Instrument and 6-Axis Stage

B. Verification Machine

Figure 7 illustrates the verification machine developed as part of this research endeavor. This machine is outfitted with the AMU-3002B Lite sensor from Silicon Sensing Systems Japan Ltd., which is capable of measuring angle, angular velocity, and acceleration. However, for the purposes of this study, only acceleration data is utilized. Additionally, the top section of the verification machine features a connection point for interfacing with a measuring instrument. Furthermore, as depicted in Figure 8, the tire connection section includes a coupling mechanism between the shaft fixing base and the pin. Irrespective of which tire components are connected, the following dimensions are maintained: $d_b = d_f = 50$ mm, $d_r = d_l = 40$ mm.

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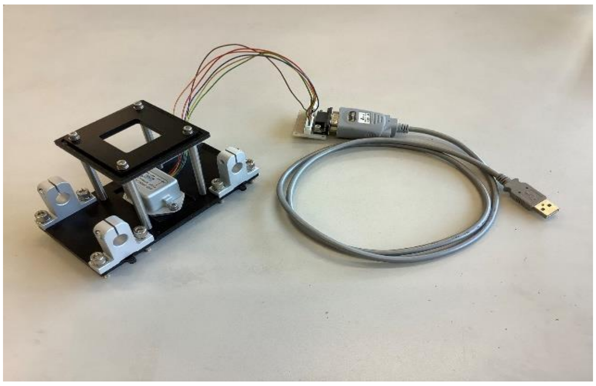

Fig. 7: Verification Machine

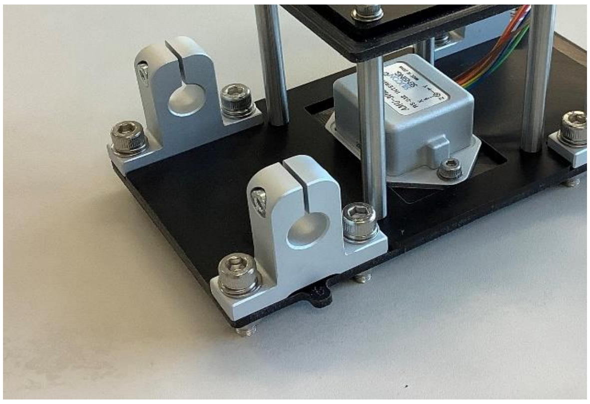

Fig. 8: Connection Part of Verification Machine

For this verification process, three types of tires were prepared: a point contact pin for establishing contact directly beneath the tire with the interior of the pipe, a line contact disc to assess potential misalignment of contact points on the tire's front or rear, and commercially available tires to examine tire side contact via tire bulge. Additionally, to evaluate the impact of tire size, two-point contact pins and two-line contact discs were prepared to match commercially available tires with pipe diameters of 150 mm and 200 mm. Figures 9 to 14 depict the verification machine with each part connected.

The radius of the tire is adjusted to 41.5 mm for the 150 mm tire and 47.5 mm for the 200 mm tire, with the length of the point contact pin also adjusted to match the radius. Moreover, the tips of the point contact pins are spherical, each with a radius of 0.2 mm. The line contact disc has a uniform thickness of 2 mm in both cases.

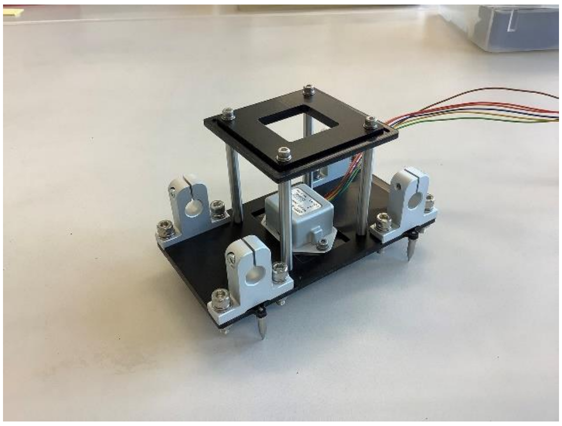

Fig. 9: Verification Machine Equipped with 150 Mm Compatible Point Contact Pins

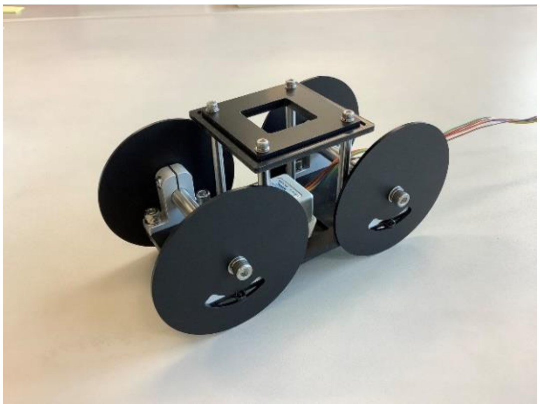

Fig. 10: Verification Machine Equipped with 150 Mm Compatible Line Contact Disc

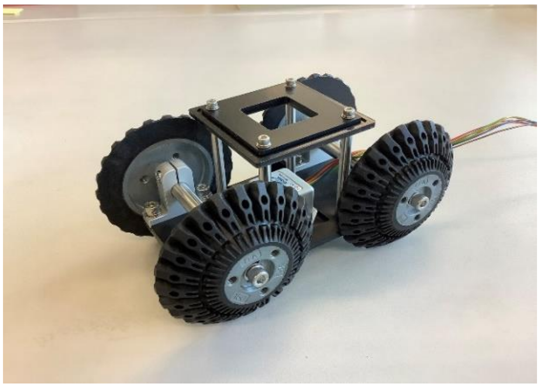

Fig. 11: Verification Machine Equipped with 150 Mm Compatible Commercial Tires

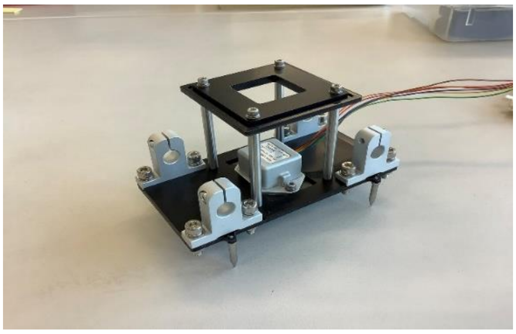

Fig. 12: Verification Machine Equipped with 200 Mm Compatible Point Contact Pins

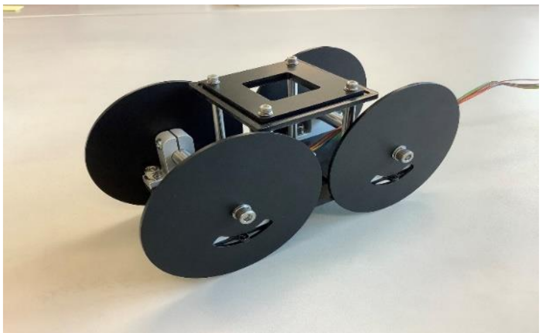

Fig. 13: Verification Machine Equipped with 200 Mm Compatible Line Contact Disc

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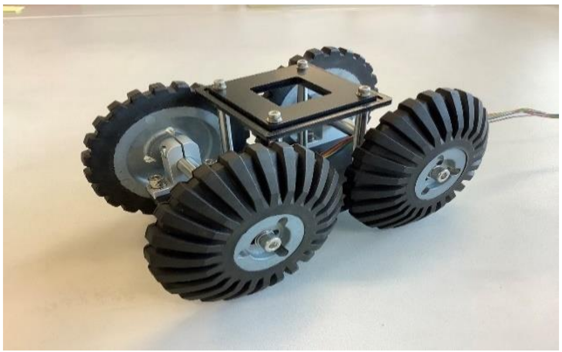

Fig. 14: Verification Machine Equipped With 200 Mm Compatible Commercial Tires

IV. VERIFICATION OF INFLUENCE OF TIRE SHAPE

To assess the impact of tire shape on the robot's localization, a test area was established at the base of the measuring instrument, as depicted in Figure 15. Following the calibration of the measuring instrument using a 6-axis stage, the mounting position on the frame was adjusted to the right and installed such that the center of the pipe, serving as the origin of the test area, was directly underneath. Anticipating comparative verification under consistent environmental conditions and significant potential variations in the robot's posture, the test area utilized piping with an inner diameter of 189.5 mm, corresponding to a nominal diameter of 200A. It's important to note that the inner diameter of the pipe deviates slightly from the standard due to the pipe being halved.

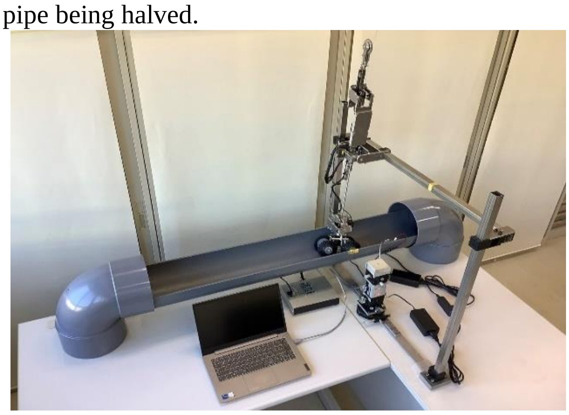

Fig. 15: Verification Test Field

Table 1 presents the measurement data and localization data. For verification purposes, the difference data from Table 1 is presented in Table 2, along with corresponding graphs depicted in Figure 16 and Figure 17. It is important to note that, given the homemade nature of the measuring instruments and the verification machine used in this study, errors stemming from processing and assembly, as well as installation inaccuracies, are more pronounced compared to commercially available products.

Consequently, when considering the dataset as a whole, the y component exhibits a shift of approximately -2.0 mm, the z component a shift of about 0.5 mm, and the β component a shift of roughly -1.0 degree. Taking these factors into account, it is observed that errors in the z and γ components of commercially available tires are significant. This is primarily attributed to the tire's side making contact with the interior of the pipe, resulting in considerable shifts in the robot's posture due to tire bulge. Notably, the errors in the z component value are more pronounced in Figure 17 compared to Figure 16, attributable to the larger tire size. Furthermore, with regards to the line contact disc, errors are observed in the y component of Figures 16 and 17 when the robot is tilted significantly in the γ direction, suggesting that the contact point deviates from directly beneath the tire in the front and rear directions. In light of these observations, it is verified that tire shape exerts a notable influence on the robot's localization. Moreover, it is evident that localization accuracy reaches a practical level when the influence of tire shape is disregarded.

Table-1: Measurement Data and Localization Data

Tire		Measurement Data					Estimated Data				
Diameter [mm]	Shape	y [mm]	z [mm]	α [degree]	β [degree]	γ [degree]	y [mm]	z [mm]	α [degree]	β [degree]	γ [degree]
150	point	-4.70	-38.54	-18.90	2.83	-15.76	-2.44	-38.93	-19.13	4.02	-17.10
150	point	0.79	-40.52	-7.37	2.85	-9.14	1.38	-40.95	-7.74	3.71	-9.20
150	point	-8.28	-40.66	-15.71	0.21	-7.11	-7.51	-41.42	-16.07	1.20	-5.70
150	point	5.75	-41.64	14.77	0.83	3.09	6.96	-42.11	14.68	1.19	5.20
150	point	3.61	-40.02	18.32	2.15	9.18	5.03	-40.14	18.42	2.49	11.70
150	line	-2.39	-39.02	-15.93	2.96	-13.18	-1.43	-39.47	-16.14	4.12	-14.80
150	line	-0.58	-40.39	-9.61	2.65	-9.11	0.12	-41.28	-9.83	3.56	-9.80
150	line	-0.96	-42.10	-4.20	1.25	-4.53	0.44	-42.50	-4.43	1.96	-4.60
150	line	-4.96	-39.91	9.39	3.86	9.86	-1.38	-40.31	9.21	4.20	10.80
150	line	-2.67	-39.53	13.08	3.75	11.51	0.26	-40.06	12.85	4.13	12.60

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150	surface	-1.74	-37.32	-17.86	3.54	-14.67	-0.92	-38.27	-18.14	4.89	-18.50
150	surface	-1.52	-37.73	-16.06	3.48	-13.43	-0.56	-39.00	-16.36	4.79	-16.70
150	surface	1.35	-41.57	6.71	0.80	2.82	1.98	-43.09	6.28	1.27	3.40
150	surface	1.07	-38.37	16.90	3.23	11.20	2.91	-39.65	17.41	3.44	13.90
150	surface	2.93	-37.44	23.86	2.69	13.80	5.32	-38.03	24.40	2.78	19.00
200	point	-4.50	-34.21	-16.19	1.55	-10.18	-2.42	-34.89	-16.38	2.69	-11.00
200	point	-1.90	-35.05	-9.35	1.86	-7.42	-0.32	-35.59	-9.59	2.62	-7.50
200	point	-6.59	-35.43	-14.59	0.40	-5.45	-5.24	-36.48	-14.82	1.31	-5.70
200	point	-0.44	-34.90	12.36	2.32	6.98	1.15	-35.27	12.26	2.71	8.80
200	point	-0.54	-34.10	15.44	3.01	9.98	1.01	-34.57	15.48	3.35	12.30
200	line	-2.58	-34.32	-14.73	2.06	-9.71	-1.39	-34.47	-15.07	3.03	-11.10
200	line	-6.25	-34.71	-17.79	0.99	-8.06	-4.58	-35.00	-18.05	1.87	-9.30
200	line	-1.70	-35.87	-6.02	1.45	-5.68	-0.18	-37.02	-6.22	2.08	-5.30
200	line	0.11	-36.11	10.15	1.32	4.14	2.27	-36.81	9.90	1.69	5.30
200	line	-1.10	-35.17	11.74	2.17	7.39	1.38	-35.84	11.55	2.47	7.90
200	surface	-3.54	-30.00	-17.99	2.46	-10.12	-1.02	-33.68	-18.24	3.69	-15.30
200	surface	-6.17	-31.57	-16.84	0.75	-5.64	-4.55	-35.21	-17.14	1.80	-8.50
200	surface	-4.95	-32.93	-11.00	0.24	-2.77	-4.57	-36.95	-11.38	0.99	-3.60
200	surface	-0.33	-31.59	12.24	2.19	5.92	1.46	-35.61	12.14	2.53	8.30
200	surface	0.11	-30.27	18.32	3.06	9.33	1.70	-33.98	18.25	3.28	14.10

Table-2: Difference Data

Tire		Absolute Error				
Diameter [mm]	**Shape**	***y* [mm]**	***z* [mm]**	**α [degree]**	**β [degree]**	**γ [degree]**
150	point	-2.26	0.39	0.23	-1.19	1.34
150	point	-0.59	0.43	0.37	-0.86	0.06
150	point	-0.77	0.76	0.36	-0.99	-1.41
150	point	-1.21	0.47	0.09	-0.36	-2.11
150	point	-1.42	0.12	-0.10	-0.34	-2.52
150	line	-0.96	0.45	0.21	-1.16	1.62
150	line	-0.70	0.89	0.22	-0.91	0.69
150	line	-1.40	0.40	0.23	-0.71	0.07
150	line	-3.58	0.40	0.18	-0.34	-0.94
150	line	-2.93	0.53	0.23	-0.38	-1.09
150	surface	-0.82	0.95	0.28	-1.35	3.83
150	surface	-0.96	1.27	0.30	-1.31	3.27
150	surface	-0.63	1.52	0.43	-0.47	-0.58
150	surface	-1.84	1.28	-0.51	-0.21	-2.70
150	surface	-2.39	0.59	-0.54	-0.09	-5.20
200	point	-2.08	0.68	0.19	-1.14	0.82
200	point	-1.58	0.54	0.24	-0.76	0.08
200	point	-1.35	1.05	0.23	-0.91	0.25
200	point	-1.59	0.37	0.10	-0.39	-1.82
200	point	-1.55	0.47	-0.04	-0.34	-2.32
200	line	-1.19	0.15	0.34	-0.97	1.39
200	line	-1.67	0.29	0.26	-0.88	1.24
200	line	-1.52	1.15	0.20	-0.63	-0.38
200	line	-2.16	0.70	0.25	-0.37	-1.16
200	line	-2.48	0.67	0.19	-0.30	-0.51
200	surface	-2.52	3.68	0.25	-1.23	5.18
200	surface	-1.62	3.64	0.30	-1.05	2.86
200	surface	-0.38	4.02	0.38	-0.75	0.83
200	surface	-1.79	4.02	0.10	-0.34	-2.38
200	surface	-1.59	3.71	0.07	-0.22	-4.77

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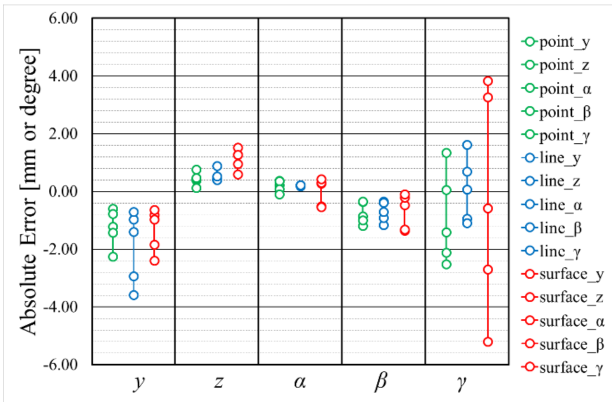

Fig. 16: Difference Data for 150 mm

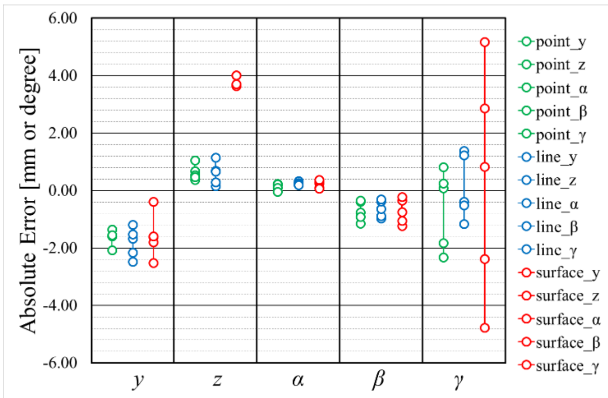

Fig. 17: Differential Data for 200 mm

V. CONCLUSION

In this paper, we investigated the impact of tire shape on the localization accuracy of a pipe inspection robot. Our findings suggest that while tire shape does indeed affect the localization method, it remains sufficiently practical when assuming direct contact beneath the tire within the pipe. Specifically, significant errors were observed in the z-axis and γ-axis directions, primarily due to the side surface of the tire making contact with the interior of the pipe. Additionally, there was a noticeable error in the y-axis direction caused by lateral tire displacement along the x-axis, albeit to a lesser extent compared to the former scenario. Based on these findings, our future research aims to develop localization methods that account for the influence of tire shape, thereby enhancing accuracy and robustness in pipe inspection applications.

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Ethical Approval and Consent to Participate	No, the article does not require ethical approval and consent to participate with evidence.
Availability of Data and Material	Not relevant.
Authors Contributions	I am only the sole author of the article.

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