Design System of Structural Health Monitoring System Using Wireless Sensor Network

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Keywords: SHMS, WSN, Web Based Monitoring, Static Routing, Linear Communication Topology.

Abstract: This research discusses a system design of a Structure Health Monitoring System (SHMS) using Wireless Sensor Network (WSN) which has successfully performed its main function of reading sensor data from each node for web based monitoring. The system consists of 4 types of sensor which are temperature humidity sensor (DHT11), Accelerometer Gyro sensor (GY521), strain sensor (Load Cell), and two kinds of displacement sensor (TOF and US100). The microcontroller used is WemosD1 mini and ESP32. The system works with a linear communication topology with a static routing protocol. Active alarms that indicate if the sensor values exceed the upper or lower limits of the system is successfully carried out. The error of the testing which carried out by DHT 11 sensor is below 2.3%. While the testing error of the GY521 is below 7%. 0.58% is the error for load cell. And the overall error of TOF and US100 is below 1%. For latency data reading on the website at the DHT11, GY521, Load Cell, TOF, and US100 sensors are 4.35%, 1.96%, 4.68%, 2.11%, and 7.68%. The latency data varies due to data transmission errors from nodes and internet network instability for the website.

1 INTRODUCTION

Bridges are an example of complex infrastructure in structures from civil engineering. Infrastructure cannot be easily predicted in the event of damage or anomalous conditions. The cause of infrastructure damage that needs to be considered is the loss of life. According to research (Amalina, 2016), there are several bridge infrastructure damage events that cause casualties, including an incident that occurred in Nepal on December 25, 2007. On that day, the Chhinchu Suspension Bridge, which is 187 meters long, was overloaded as a result resulting in 13 dead and 32 injured. Furthermore, the collapse of the Kutai Kertanegara Bridge on November 26, 2011 is an incident that shows how important monitoring and scheduled maintenance are on a bridge. The incident on the Kutai Kertanegara Bridge was caused by a load that exceeded the limit passing through the bridge (Arifin, 2014).

These events may be avoided if the party concerned implements a system with technology that is able to monitor the condition of the bridge as has been applied in developed countries. The technology is the Structural Health Monitoring System (Arifin, 2014). According to research (Hartono, 2001) SHMS is a system used to observe all matters relating to the operation and monitoring of structural health conditions, helping to take corrective action through manual or automatic commands by several existing devices. Based on communication, SHMS on bridges is divided into two types, namely wired and wireless SHMS technology. This cable-based technology has the advantage that the data sent back by the sensor is very accurate and no additional electrical power is required when the sensor is operating because electrical power has been provided by the control center. However, cable-based technology also has limitations, such as the need for cabling, where installation is a complicated job.

To reduce the cost of cabling and the number of components used, the most suitable solution is to use a Wireless Sensor Network (WSN) in the SHMS system (Amalina, 2016). WSN is a network consisting of several sensors in different locations. This allows sensors to perform monitoring processes on certain objects and transmit data wirelessly (Cahya, 2016). WSN is formed from a set of small autonomous devices with several sensors contained in it, so this device is called a sensor node (Sutaya, 2019).

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The topology and architecture of a Wireless Sensor Network (WSN) generally depends on the geographical area where the sensors are placed. A Linear Wireless Sensor Network (LWSN) is a special case, where the physical topology of the network is a line. The applications of LWSN are diverse, e.g. monitoring of large infrastructure such as bridges and dams, road traffic observation, and border control (Domga, 2019).

So this research will make about "Designing Structural Health Monitoring System Using Wireless Sensor Network" as an alternative solution to the above problems. In this study, bridge supervisors are made easier to monitor and control the bridge because it can be monitored via the website, bridge control is also made easier because monitoring can be real time so that it is like in research (Abadi, 2020), which has been able to facilitate officers in maintaining and supervising building resources remotely, and for the output of each sensor there will be an alarm on the website indicating that the bridge condition is critical according to the threshold that can be adjusted according to the bridge environment. In WSN routing, a communication protocol is needed between nodes. For this protocol was chosen because of research (Abadi, 2020), in his research using static routing because in his research it is explained that this type of routing is suitable for small-scale and non-moving networks and in finding information about the intended network is configured manually by the admin or network manager. In this research, the network is small-scale and non-moving so it is suitable to use a static routing protocol and manual configuration is used to change the path if the sending node is being turned off by the bridge supervisor or the sending node is in maintenance.

2 SOLUTION METHOD

This section will explain the system design, system flow diagram and system architecture.

2.1 System Design

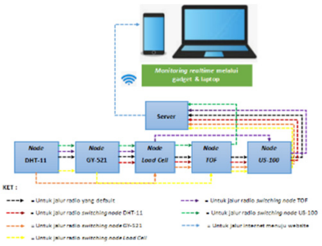

Figure 1: System Overview.

Figure 2.1 describes the system designed for monitoring data sent from each node installed linearly as shown in Figure 2.1. The communication uses radio signals that use Nrf24l01 as the module.

Then the data that has been collected according to the predetermined path according to Figure 2.1, the data is forwarded to the server. Once received, the data continues to the website for monitoring in real time which can be accessed via laptop or gadget by the user. Monitoring that can be done includes: critical condition alarms, real-time sensor readings, and node alarms that are being turned off by bridge supervisors or in maintenance.

2.2 System Flowchart

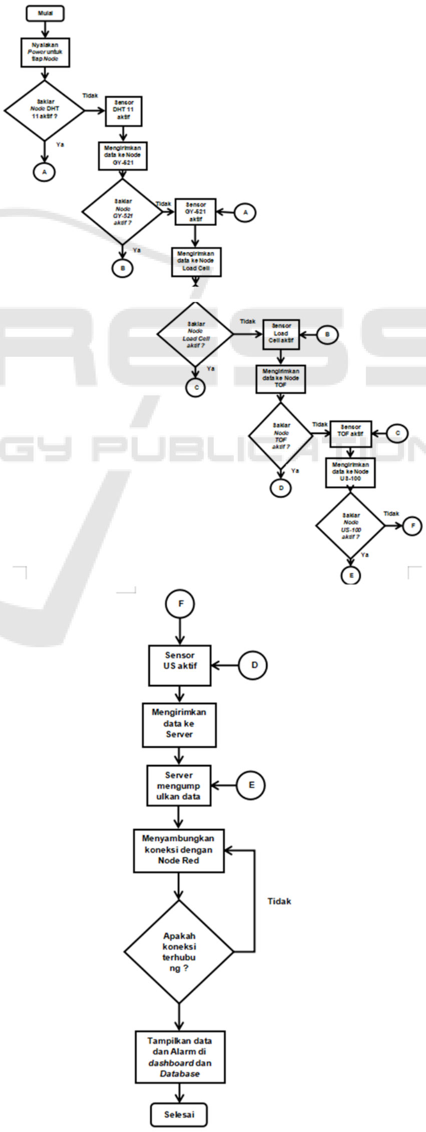

Figure 2: Flowchart of Control System.

Figure 2 describes the flow chart of the microcontroller used to process data from each sensor collected on the server for monitoring on the dashboard and database. The first stage is turning on the power for each sensor node. The next stage is to check the switch on each sensor node whether it is on or not, if it is on then the next sensor will automatically activate and continue the existing data before the node whose switch is active, otherwise the node will continue according to the flow chart in Figure 2.2. Finally, the server that has collected the data checks the connection to Node-Red, if connected, the data will be displayed on the dashboard and database using MySQL.

2.3 System Architecture

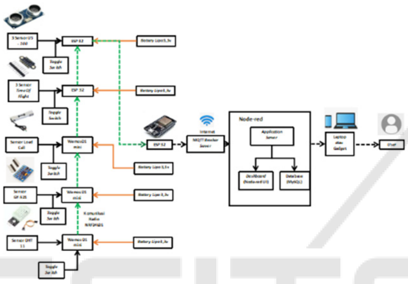

Figure 3: System Architecture.

The figure 3 explains the system architecture starting from the contents of each node to the sensor reading on the website by the user. The SHMS monitoring control system uses 5 types of sensors, namely: 3 axis time of flight sensors and 3 axis ultrasonic for displacement detection (position movement), GY-521 sensors for tilt and vibration detection, DHT 11 sensors to detect temperature, and load cells to detect weight on the bridge. The data will be processed by the WemosD1 mini microcontroller and ESP32 which gets power from a battery. Furthermore, the data will be sent with a linear topology and state routing protocol using a toggle switch. For sending to the server using Nrf24l01 radio signal.

Then, the data will be received by ESP32 as a microcontroller on the server. Through the internet line, the data will proceed to the MQTT Broker Server and then enter the Node-red which aims to monitor the system on the dashboard and database, then the data that has been stored is forwarded to a website that can be accessed by a gadget or laptop online. Finally, users can monitor data from sensors via a laptop or gadget to the website, where what can be accessed is an alarm when the sensor reading exceeds the predetermined upper and lower limits and real-time sensor data readings to see the state of the bridge in real time. There is also a user who gets access to be an admin, who can excessively change the upper and lower limits for each sensor.

3 EXPERIMENTAL RESULTS AND DISCUSSION

3.1 DHT 11 Sensor Test

Table 1: DHT11 Sensor Test.

No	DHT11		HTC-01		Error(%)	
	Temp (C°)	Humidity (%)	Temp (C°)	Humidity (%)	Temp	Humidity
1	24,7	81	24,3	83	1,65	2,41
2	25,7	73	25,1	75	2,39	5,67
3	9,1	61	9,2	63	1,09	3,17
4	24,4	87	23,2	92	5,17	5,43
5	29,4	50	30	43	2	16,28
6	25	74	24,1	80	3,73	7,5
7	25,3	76	24,2	79	4,55	3,8
8	24,9	73	24,5	78	1,63	6,41
9	24,6	75	24,6	78	0	3,85
10	24,4	74	24,6	77	0,81	3,9
Average Error					**2.3**	**2.27**

In this test, it is carried out to determine the uncertainty value of a device that will be used. The value obtained from this test is the error value of the DHT 11 sensor reading compared to the HTC-01 value as a benchmark.

The value obtained during this 10-time test is done by comparing the DHT 11 value through the same ambient and room temperature. There is an average error value of 2.3% for temperature and 2.27% for humidity error.

3.2 GY-521 Sensor Tilt Test

This test was conducted to determine the error value of the GY-521 sensor for pitch and roll tilt readings. The error value is obtained from the GY-521 sensor reading compared to the protractor as a measuring instrument.

Testing is done by entering 9 parameter values for the angle, where each angle will be tested 3 times to get the pitch and roll error values.

The values obtained are an average error of 4.07% for the pitch angle and 6.96% for the roll angle error.

3.3 GY-521 Sensor Frequency Test

This test was conducted to determine the error value of the GY-521 sensor for frequency readings. The error value is obtained from the GY-521 sensor reading which is compared with a gadget application called Vibrations as a measuring tool.

Table 2: Test of GY-521 Sensor tilt measurement.

No	Sudut (°)	Uji ke -	GY-521		Error(%)	
			Pitch (°)	Roll (°)	Pitch	Roll
1	0	1	0	0	0,00	0,00
		2	0	0	0,00	0,00
		3	0	0	0,00	0,00
2	45	1	45,2	40	0,44	11,11
		2	41	40,3	8,89	10,44
		3	39,2	40,72	12,89	9,51
3	90	1	81,6	82,7	9,33	8,11
		2	80,8	82,5	10,22	8,33
		3	86,2	83	4,22	7,78
4	30	1	35	31	16,67	3,33
		2	28,92	29,8	3,60	0,67
		3	29,52	32,57	1,60	8,57
5	60	1	60,4	60,5	0,67	0,83
		2	60,62	66,4	1,03	10,67
		3	60,9	66,6	1,50	11,00
6	-45	1	-40,8	-41,6	9,33	7,56
		2	-42,1	-41	6,44	8,89
		3	-41,68	-41	7,38	8,89
7	-90	1	-88,58	-84,2	1,58	6,44
		2	-87,72	-84,8	2,53	5,78
		3	-88,77	-83,4	1,37	7,33
8	-30	1	-29,5	-34,5	1,67	15,00
		2	-29,72	-35,32	0,93	17,73
		3	-29,43	-33,3	1,90	11,00
9	-60	1	-58,4	-58,4	2,67	2,67
		2	-58,7	-58,2	2,17	3,00
		3	-59,41	-58	0,98	3,33
Error rata-rata keseluruhan					4,07	6,96

Table 3: Test of GY-521 Sensor Frequency measurement.

No	Freq (Hz)	GY-521(Hz)	Error (%)
1	7	7,43	6,14
2	5,04	5,16	2,38
3	4,42	4,92	11,31
4	5,11	5,58	9,2
5	4,3	4,37	1,63
6	6	6,98	16,33
7	5,32	5,38	1,13
8	6,2	6,52	5,16
9	1,7	1,58	7,06
10	5,9	5,98	1,36
Average Error			**6,17**

The test was carried out by entering 10 times the input obtained was an average error of 6.17% for the GY-521 sensor frequency.

3.4 Load Cell Sensor Test

In this test, it was carried out to determine the error value of the Load Cell sensor for weight reading. The error value is obtained from the GY-521 sensor reading which is compared to the scale as the measuring instrument.

Table 4: Test of Load Cell Sensor weight measurement.

No	Weight (gram)	Test No.	Load Cell Sensor	Error (%)
1	11,4	1	11,46	0,53%
		2	11,48	0,70%
		3	11,46	0,53%
		4	11,43	0,26%
		5	11,44	0,35%
2	23,7	1	23,58	0,51%
		2	23,56	0,59%
		3	23,51	0,80%
		4	23,63	0,30%
		5	23,59	0,46%
3	8,5	1	8,5	0,00%
		2	8,45	0,59%
		3	8,51	0,12%
		4	8,5	0,00%
		5	8,52	0,24%
4	18,1	1	18,22	0,66%
		2	18,2	0,55%
		3	18,26	0,88%
		4	18,2	0,55%
		5	18,26	0,88%
5	10,9	1	10,77	1,19%
		2	10,81	0,83%
		3	10,78	1,10%
		4	10,79	1,01%
		5	10,8	0,92%
Average Error				**0,58%**

The test is conducted by entering 5 values for weight in grams, where each angle will be tested 5 times to get the weight error value.

The value obtained is an average error of 0.58% for the Load Cell sensor.

3.5 TOF and US-100 Sensor Testing

This test was conducted to determine the error value of the readings of the 3 TOF and US-100 sensors compared to the ruler as a test tool.

Table 5: TOF Sensor Testing and US-100 distance measurement.

No	Distance (mm)	Test No.	TOF Sensor			US-100 Sensor		
			X-Axis	Y-Axis	Z-Axis	X-Axis	Y-Axis	Z-Axis
1	100	1	96	101	100	100	94	96
		2	95	98	97	102	96	100
2	200	1	205	205	198	201	200	199
		2	201	200	204	200	204	201
3	300	1	295	303	304	299	301	300
		2	301	304	299	303	296	297
4	400	1	402	400	403	403	393	400
		2	401	397	400	405	403	400
5	500	1	500	502	497	495	500	502
		2	502	499	502	503	501	496
6	600	1	601	599	604	603	602	598
		2	599	597	601	602	600	595
7	700	1	700	706	710	712	699	698
		2	704	703	708	704	702	706
8	800	1	803	801	796	803	803	817
		2	805	798	804	805	799	800
9	900	1	904	898	903	905	904	910
		2	894	903	898	902	901	896
10	1000	1	1010	1020	1005	1014	1004	1008
		2	1005	1007	1012	1009	1006	1001
Average Error			**0,98%**	**0,74%**	**0,80%**	**0,73%**	**0,96%**	**0,73%**

Tests were carried out by entering 10 values for the distance in mm, where each distance will be tested twice to get the distance error value for 3 TOF sensors x, y, z axis and 3 US-100 sensors x, y, z axis.

The values obtained are the average error for TOF x, y, and z axes which are 0.98%, 0.74%, and 0.8%. As for the US-100 x, y, and z axes, the reading errors are 0.73%, 0.96%, and 0.73%.

3.6 Latency Testing of Data Reading for Each Node on the Website

Testing is done to get the latency or delay reading value for each node that is read in the Node-red dashboard. The reading is done using a stopwatch available on the gadget, where the stopwatch is turned on when the data is read until the next data is read.

Table 6: Latency Testing of Data Reading for Each Node on the Website.

No	Test No.	Delay (second)				
		Node DHT-11	**Node GY-521**	**Node Load Cell**	**Node TOF**	**Node US-100**
1	1	2,16	0,63	3,6	0,59	8,98
2	2	10,28	4,43	5,38	0,98	4,93
3	3	1,67	0,88	2,25	0,69	3,26
4	4	1,32	0,39	8,17	3,27	6,74
5	5	5,41	4	4,01	0,44	6,43
6	6	2,43	0,5	1,94	3,32	8,68
7	7	2,88	3,93	3,91	2,91	21,02
8	8	9,88	1,01	6,75	5,02	3,43
9	9	5,1	2,15	7,9	2,91	4,37
10	10	2,41	2,21	2,87	0,95	8,92
Average Error		**4,35**	**2,01**	**4,68**	**2,11**	**7,68**

Testing was carried out 10 times and there were 5 nodes, namely DHT 11, GY-521, Load Cell, TOF, and US-100 nodes where the average latency in order was 4.35%, 1.96%, 4.68%, 2.11%, and 7.68%.

3.7 Latency Testing of Switch Alarm Reading for Each Node on the Website

Testing is done to get the latency value or reading delay for the switch alarm for each node that reads the alarm on the Node-red dashboard which indicates the switch is doing its job properly. The reading is done using a stopwatch available on the gadget, where the stopwatch is turned on when the switch is turned on until the alarm is read.

Testing was carried out 10 times and the nodes that used the switch were 5 nodes, namely the DHT 11, GY-521, Load Cell, TOF, and US-100 nodes where the average latency readings in order were 8.4%, 17.645%, 9.847%, 11.06%, and 16.244%.

Table 7: Latency Data & Transmission.

No	Test No.	Delay (second)									
		Node DHT-11	Desc	Node GY-521	Desc	Node Load Cell	Description	Node TOF	Description	Node US-100	Description
1	1	6,64	S	23,99	S	24,89	S	12,55	S	3,94	S
2	2	6,56	S	29,84	S	15,38	S	36,92	S	6,98	S
3	3	12,23	S	11,08	S	1,35	S	23,05	S	27,45	S
4	4	9,16	S	23,22	S	3,74	S	2,78	S	6,65	S
5	5	5,07	S	5,5	S	31,76	S	4,28	S	2,79	S
6	6	4,5	S	17,2	S	2,44	S	9,09	S	31,48	S
7	7	15,91	S	35,72	S	5,07	S	4,71	S	12,14	S
8	8	5,99	S	13,83	S	6,77	S	6,32	S	50,18	S
9	9	12,63	S	6,8	S	3,6	S	6,93	S	14,81	S
10	10	5,31	S	9,27	S	3,47	S	3,97	S	6,02	S
Average		8,40		17,65		9,85		11,06		16,24	
S = Succesfull US = Unsuccesfull											

4 CONCLUSIONS

Based on the results of the design and testing of the monitoring system for bridge health, it has successfully performed its main function, namely reading sensor data from each node for monitoring and reading the switch alarm which is a static routing protocol system that is used if the node is turned off due to problems or maintenance, then there is also history data on the dashboard of each node which is intended for bridge supervisors and bridge engineers to view past data. Where when testing the error from the DHT 11 sensor is below 2.3%. Then for the GY-521 error which is below 7%. Furthermore, the Load Cell sensor has an error of 0.58%. And the last sensor test is the distance on TOF and US-100 where the overall error is below 1%.

For data reading latency at each node on the website at nodes DHT 11, GY-521, Load Cell, TOF, and US-100 where the average latency in order is 4.35%, 1.96%, 4.68%, 2.11%, and 7.68% then the latency of the switch alarm reading data is node DHT 11, GY-521, Load Cell, TOF, and US-100 where the average latency readings in order are 8.4%, 17.645%, 9.847%, 11.06%, and 16.24% where latency data varies due to data transmission errors from nodes and internet network instability for the website.

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