Integrated Sensing Systems and Algorithms for Solid Waste Bin State Management Automation

Article *in* IEEE Sensors Journal · November 2014

DOI: 10.1109/JSEN.2014.2351452

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Integrated Sensing Systems and Algorithms for Solid Waste Bin State Management Automation

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***Abstract*— Intelligent solid waste bin is essential to develop an efficient and dynamic waste management system. This research presents the implementation and execution of an integrated sensing system and algorithm for solid waste bin to automate the solid waste management process. Several sensing methods have been integrated and have combined their verdicts that offer the detection of bin condition and its parameter measurement. A number of test runs have been conducted to assess the functioning of the prototype system. The outcomes showed that the sensing system with the algorithm is efficient and intelligent and can be simply used to automate any solid waste bin management process.**

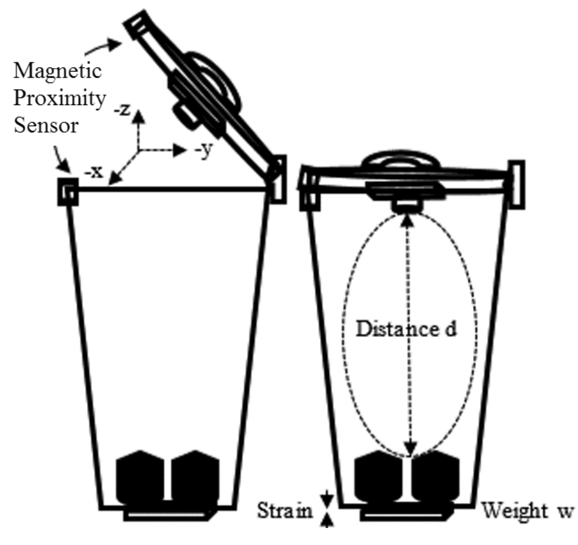
***Index Terms*— Automation, integrated sensing system, solid waste management.**

I. Introduction

An INTELLIGENT solid waste bin operates to ensure the efficient measurement of its status while consuming minimum energy. At present, major cities around the world require challenging solutions for solid waste management (SWM), as a result of growth in residential areas and the economy. SWM is a costly urban service that consumes around 20% - 50% of municipality's annual budget in developing countries. Furthermore, 85% of solid waste management funds are spent on waste collection and transportation [1]. It becomes an excessive wastage of resources when bins are collected that are filled up partially. In waste collection and carrying activities, the operational cost can be reduced by optimizing the quantity and deployment of collection bins and their collection rate [2]–[4]. Estimating the status with waste level and weight of waste inside bins help to optimize collection routes and improve collection efficiency.

A SWM system having static scheduling and routing to collect waste demands more operating costs, longer hauling distances and increased labor hours compared to a system with dynamic scheduling and routing attitude [5]–[7]. In [5] and [6], the authors calculated a potential cost savings of 10-20% and transport mileage savings of 26% when dynamic scheduling and routing were used. For a truly dynamic and automatic system, it is important to know the current and actual fill level of a bin rather than a prediction relays on historical fill level data, which arises questions as 'when will the bin be at an enough fill level to stick up for collection?'. So, to implement a SWM system with dynamic scheduling and routing for waste collection, it is very useful and important to get real time data about the bin status. Several researches have been done over the last few decades concerning solid waste monitoring and management. But a few of them dealt with real time bin status data with a motive to implement dynamic scheduling and routing approach for an automatic solid waste management system. Table I shows a list of related work with their advantages and limitations.

In [8] and [9], the authors estimate the bin filling level by capturing and processing bin's image. The system can capture the image when the waste collection vehicle reached in the vicinity of the bin. As the control center does not get the real time bin status data, it depends on the historical data for the collection route. In [10] and [11], the researchers developed a bin by using several types of sensor like light-emitting diode (LED), camera, ultrasonic, pressure etc. for early detection of the bin status. But the system cannot respond instantly when waste is thrown inside the bin. The authors in [12], reports a system that have not sufficient information about the bin level measurement techniques and the dynamicity. In [5], the authors present a system for remote monitoring of



(a) (b)

Fig. 1. (a) Lid status sensing. (b) Waste filling level and weight sensing.

Manuscript received July 9, 2014; accepted August 9, 2014. Date of publication August 28, 2014; date of current version November 11, 2014. This work was supported Grant LRGS/TD/2011/UKM/ICT/04/01, Grant PRGS/1/12/TK02/UKM/02/2, and Grant DIP-2012-13. The associate editor coordinating the review of this paper and approving it for publication was Dr. M. R. Yuce.

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Digital Object Identifier 10.1109/JSEN.2014.2351452

TABLE I
RELATED WORKS WITH THEIR ADVANTAGES AND LIMITATIONS

Related Literature	Filling Level Measurement	Filling Level Measurement Technique	Weight Measurement	Real Time Response	Scheduling and Routing Consideration
[8][9]	Yes	Image Processing	No	No	No
[10]	Yes	Ultrasonic	Yes	No	No
[11]	Yes	Ultrasonic	No	No	Yes
[12]	Yes	Unknown	No	Yes	No
[5]	Yes	Infrared Image Sensing	No	No	Yes
[6]	Yes	Infrared LED	No	Yes	Yes
[7]	Yes	Infrared	No	No	Yes

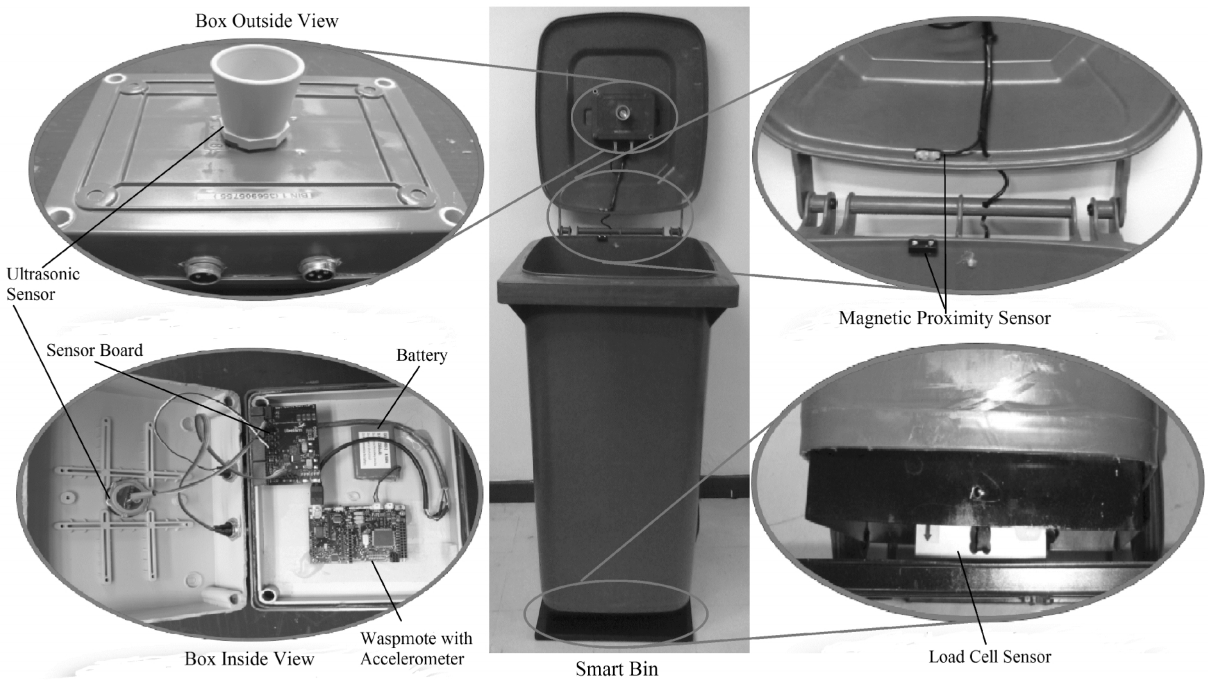

Fig. 2. Smart bin prototype.

materials disassembled from end-of-life vehicles. Both solid and liquid materials were placed in containers and fill levels were measured by using infrared image sensing. The system response is not real time. A system for collecting cardboard waste is developed in [6], where the researchers used LED to measure the container level. The system was activated once an hour to measure the fill level and raised an alarm if a certain level was exceed. To dynamically optimize the collection route in charity sector, textile banks were developed in [7], where the top of the donated textiles pile inside a bank was measured by installing an infrared sensor underside of the roof of each bank. The server got updated data in every 12 hours. This work present a concept to integrate several sensing technologies and algorithms to design a smart bin as a way to implement an automatic, dynamic and real time SWM system.

II. INTEGRATED SENSING SYSTEMS

The developed automatic system offers the real time bin status data from three sensing systems: lid status sensing, waste level sensing and weight sensing. Explicit of the individual systems are described below.

A. Lid Status Sensing

The functional structure of the lid status sensing system is implemented for tracking the initialization of waste loading and unloading event and perceiving the overflow status of the bin as shown in Fig. 1(a). Accelerometer sensor data are accumulated to provide the drift and its direction to identify the opening/closing of the lid. The acceleration A is defined as follows [13]:

$$A = (A_x, A_y, A_z) \tag{1}$$

where A_x , A_y and A_z are the acceleration towards x, y and z axis. The magnetic proximity sensor reports whether the lid closed properly or not by using a reed switch and a permanent magnet. The switch can change it’s state due to magnetization or biasing caused by the magnet when a conductor attached in the lid enters into the magnetic field mounted in the upper

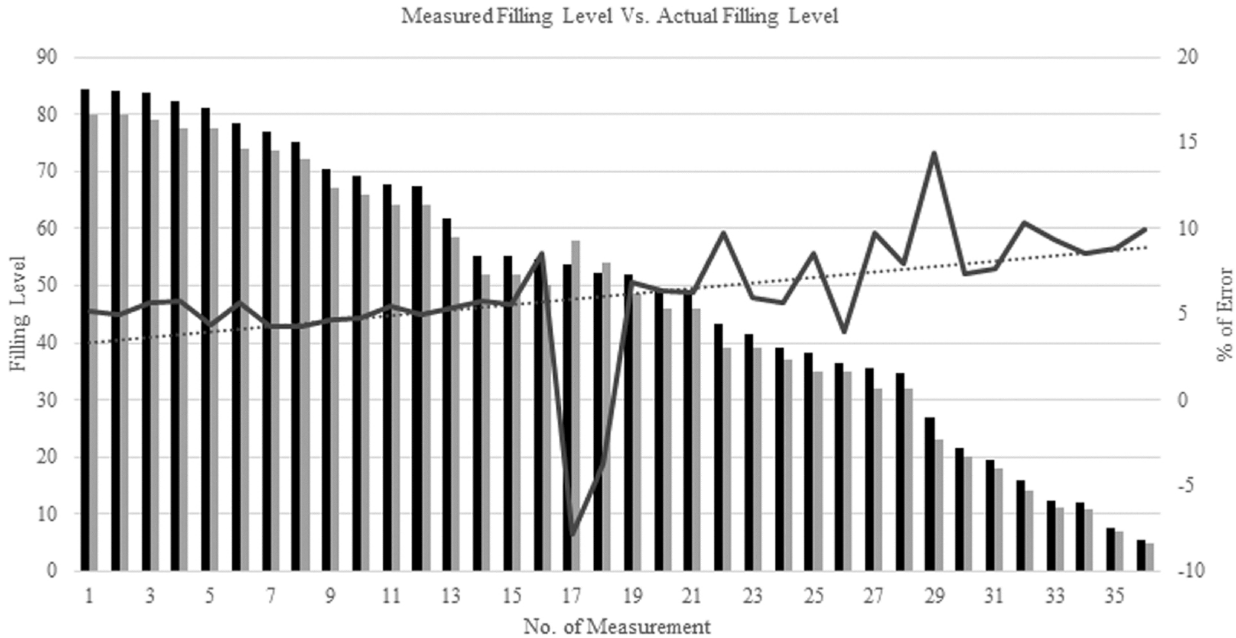

Fig. 3. Measured filling level versus actual filling level and percentage of error.

TABLE II
POWER CONSUMPTION BY THE MOTE AND SENSORS

Device	Active Mode	Idle Mode
Waspmote	15 mA	55 μA
Sensor Board	5 μA	5 μA
Accelerometer	250 μA	10 μA
Proximity Sensor	33 μA	No (Off)
Ultrasonic	3.4 mA	No (Off)
Load Cell	16.4 mA	No (Off)

TABLE III
HARDWARE COMPONENTS COSTS OF THE SMART BIN

Component	Unit Price ($)
Waspmote and Accelerometer	180
Sensor Board	130
Magnetic Proximity Sensor	15
Ultrasonic	125
Load Cell	65
Battery	20
Bin	15
Accessories (Box, foil, Wire, Screw etc.)	10

edge of the bin. More information about magnetic proximity sensing can be found in [14].

B. Waste Filling Level Sensing

The sensing of waste filling level inside a bin is based on the measurement of the time-of-flight i.e. the complete return trip time, an ultrasonic pulse takes to transmit and receive its reflected echo between the sensor and the sensed material level [15] as shown in Fig. 1(b).

C. Weight Sensing

The weight estimation of the waste inside a bin is based on the principle of an electrical conductor whose resistance changes when its length changes due to stress and it is virtually proportional to the applied strain as shown in Fig. 1(b). A Wheatstone Bridge Network is built by using at least four strain gauges with four separate resistors. Waste inside the bin causes a variation in value of one or more resistors due to the generated strain from the metallic member that contains the strain gauges. Thus, the bridge output voltage is changed with this variation in resistance that is proportional to the weight of the waste [16].

III. SENSING ALGORITHMS

Generally the whole sensing system remains in the sleeping mode except the accelerometer, which remains in the inertial wake up mode. This ensures the minimum consumption at idle state. When someone opens the lid of the bin, the accelerometer sensor sends interrupt to wake up the system. After awaken, the following rules are used to perceive the bin status and measure the bin parameters.

1) If ΔA_y, ΔA_z and $P_l = 1$, then the bin is in loading situation and the lid is opened from closed position.
2) If ΔA_y, ΔA_z and $P_l = 0$, then the bin is in loading situation and the lid is closed from opened position.
3) If ΔA_x, ΔA_y, ΔA_z and $P_l = 0\, or\, 1$ then the bin is in unloading situation.

In the above, ΔA_x,ΔA_y and ΔA_z are the change of acceleration due to the change of magnitude of the x, y and z axis of the accelerometer and P_l is the proximity sensor value. The minimum change of value for any axis is estimated for this application is ± 0.11g to interrupt the sleeping sensing unit.

TABLE IV
EXPERIMENTAL DATA FROM SEVERAL TEST RUN OF THE PROTOTYPE

Test No.	X Axis Acceleration	Y Axis Acceleration	Z Axis Acceleration	Magnetic Proximity Sensor Value	Filling Level (cm)	Weight (kg)	Remaining Battery (%)	Action
1	-45	-336	-540	0	0.78	0	53	Loading
2	78	-305	-749	0	38.27	1.06	49	Loading
3	69	-344	-741	0	54.67	2.03	50	Loading
4	6	-293	-773	1	9999	5.42	56	Loading
5	-337	-572	-1075	1	-	-	56	Unloading
6	-5	-432	-862	0	0.97	0	54	Loading
7	5	-625	-763	0	12.35	0.98	53	Loading
8	-28	-278	-929	0	36.45	2.12	57	Loading
9	22	-1001	-14	0	55.08	3.59	56	Loading
10	20	-849	-495	0	61.81	4.11	57	Loading
11	-20	-367	-906	0	70.3	5.34	59	Loading
12	-27	-179	-956	0	75.21	5.88	55	Loading
13	23	2	1038	0	84.33	7.89	55	Loading
14	3	-697	-699	1	9999	9.22	57	Loading
15	-123	-883	543	1	-	-	60	Unloading
16	2	-353	-908	0	0.92	0	61	Loading
17	-45	-151	-954	0	5.55	0.76	60	Loading
18	-13	-469	-860	0	19.49	0.87	62	Loading
19	-25	-353	-902	0	26.86	1.11	62	Loading
20	17	-993	179	0	39.21	3.45	61	Loading
21	-25	-212	-949	0	41.48	3.47	60	Loading
22	6	-747	-644	0	52.06	3.92	62	Loading
23	-45	-141	-954	0	52.05	3.92	64	Loading
24	-33	-125	-957	0	53.81	3.92	61	Loading
25	-39	-398	-893	0	67.72	4.01	62	Loading
26	-17	-190	-954	0	69.3	4.17	65	Loading
27	7	-791	-585	0	82.22	4.98	62	Loading
28	13	-949	356	1	9999	5.76	67	Loading
29	-130	-821	621	1	-	-	69	Unloading
30	11	-332	-845	0	0.75	0	68	Loading
31	-32	-304	-892	0	21.59	2.19	67	Loading
32	-6	-604	-782	0	43.2	4.8	70	Loading
33	42	-607	-767	0	67.33	7.38	72	Loading
34	-30	987	124	0	81.03	10.55	78	Loading
35	10	-866	545	1	9999	13.17	74	Loading
36	432	-140	-1085	1	-	-	72	Unloading
37	-21	-299	-924	0	0.69	0	73	Loading
38	-37	-337	-874	0	11.92	1.42	72	Loading
39	-5	-336	-881	0	34.76	3.59	74	Loading
40	-58	-587	-790	0	49.05	3.94	77	Loading
41	-19	-538	-825	0	76.8	4.87	73	Loading
42	-4	-666	-722	0	83.77	4.98	77	Loading
43	-12	-61	1065	1	9999	5.22	74	Loading
44	-881	-612	-992	1	-	-	79	Unloading
45	7	-215	-949	0	0.88	0	77	Loading
46	-17	-399	-881	0	7.57	0.51	76	Loading
47	-13	-449	-859	0	15.78	1.89	77	Loading
48	2	-518	-826	0	35.45	2.34	79	Loading
49	25	-969	-227	0	49.12	3.23	79	Loading
50	43	-282	-597	0	55.2	3.87	78	Loading
51	-9	-497	-842	0	78.41	4.97	79	Loading
52	22	-985	-204	0	84.15	5.05	80	Loading
53	26	-999	-21	1	9999	5.68	79	Loading
54	384	250	-840	1	-	-	78	Unloading
55	-21	-211	-663	0	0.91	0	79	Loading

After measuring the bin operative situation and lid position, the following rules are used to detect whether the bin is overloaded or not.

4) If rule 1) satisfies and if the bin lid stays in the open state for a time that exceeds a time threshold, then the system reports that the bin is overloaded.
5) If rule 1) satisfies and if rule 2) satisfies before exceeding a time threshold, then the system reports that the bin is not overloaded.

After determining whether the bin is overloaded or not, the system activates different sensors for each condition using the following rules.

6) If rule 5) satisfies, then the system activates both the waste level sensing system and weight sensing system to measure the waste filling level and the weight of waste.
7) If rule 4) satisfies, then the system activates only the weight sensing system to measure the weight of the waste.

TABLE V
VARIATION OF ACCELERATION DATA BASED ON LID POSITION DURING LOADING OPERATIONS

Lid Position with Respect to Ground	X Axis Value	Y Axis Value	Z Axis Value
0^0	32	-24	-958
20^0	48	-313	-926
45^0	52	-541	-804
90^0	38	-998	-39
180^0	-18	-114	932
270^0	-17	996	33

According to the above algorithms, at idle time the sensing unit remains in sleeping mode. Upon opening the bin's lid, the accelerometer measures the acceleration. If a threshold value for the acceleration exceeds, then the sensing unit wakes up and measure the hall voltage. Then it estimates the lid position along with the bin's operative mode based on the direction of acceleration and magnetic proximity sensor response. The bin is in loading state if the direction of change of acceleration is in y and z axis. The change occurs in all three axis means an unloading state. At the same time the proximity value of 0 or 1 decides the lid position in closed or opened position respectively. If the lid is opened and remains that position for a specific time (10 seconds is considered for the experimental purpose), then the sensing unit determines it as overloaded. Finally, the sensing unit activates the weight sensor along with or without the ultrasonic sensor and collect the corresponding value(s). The weight sensor alone is activated when the bin is overloaded and both of these sensors are activated only when the bin is not overloaded. After perceiving and measuring the bin status data, the system transmits the data to its controller and enters into sleep mode that continues until the next interruption by the accelerometer. In this way the system can collect real time bin status data by consuming the minimum energy.

IV. EXPERIMENTAL SETUP

Using a set of carefully chosen sensors, we have implemented three prototypes of solid waste bin. For the lab experiment, this prototype is designed without considering the detailed manufacturing problems. 240L two wheels bins are used with some modifications. One group is mounted on underside of the bin's lid which are consists of the accelerometer, reed switch and ultrasonic sensors. A permanent magnet is attached in the upper edge inside the bin. The other group consists of a load cell sensor which is embed under the bin and upside of a foil attached with the bin. Waspmote and Smart Metering sensor board [17] are used to integrate the sensors that are placed at the top part of the bin inside a box. ATmega1281 chips have been employed as MCUs in this device. Fig. 2 shows the experimental setup of the system.

The LIS331DLH motion sensor [18], is used as an accelerometer for the system. It is an ultra-low power and high performance three axes linear accelerometer that has dynamically selectable full scales of $\pm 2g/\pm 4g/\pm 8g$. For this system the sensibility $\pm 2g$ is selected. In the steady state, the accelerometer produce some offset instead of the normal output of $(0,0,-g)$ in (x,y,z) axis respectively. This offset is corrected for each bin and also the gravity acceleration is considered for each readings to make the decisions. Considering the normal attitude of throwing waste and depending on the sensitivity of this accelerometer, the minimum detectable acceleration is estimated as $\pm 0.11g$ of full scale $\pm 2g$ for this application. This is done by performing several test runs where 30 persons throw waste inside the prototype under different condition.

PLA41201 is used as a proximity sensor that can act as a switch which is based on the presence or absence of a magnetic object using a critical distance. The sensor has a length, width and thickness of 32mm, 15mm and 7mm respectively [19]. U625000 magnet is used with this sensor. When the magnetic flux is passing through the broad faces of the sensor strip and the sensor carries maximum current (1A), then the number of charge carriers (N) is about 4.438×10^{25}. This sensor have a sensibility up to 13mm i.e. it can produce a voltage between 0V (low value) to 3.3V (high value) when distance between the conductor and magnet is from 0 mm to 13 mm. For this application, the critical distance between the switch and the magnet is about 5 to 6 mm i.e. the minimum gap between the lid and the bin is 5 to 6 mm to perceive a lid open information. So, within the critical distance, it produces an output of 0. Otherwise, the sensor gives an output of 1.

XL-MaxSonar-WRA1 is used as ultrasonic sensor [20], which is an outdoor and weather resistant sensor having resolution of 1cm. This sensor consumes low power while giving a detection range of 765 cm and able to perform real time automatic calibration (humidity, ambient noise, voltage). This sensor is equipped with filtering firmware which allows it to ignore noise and smaller targets and report the target with largest acoustic reflection. Despite of this characteristic, for this experiment the ultrasonic sensor produces results with some error due to the irregularities of solid waste. Fig. 3 shows a comparison of measured filling level value and actual filling level value during the test runs of the prototype. For the comparison, mixtures of different types of solid waste (paper, cardboard, plastic, ferrous metal, glass, textile etc.) are packed in 47cm × 53cm and 57cm × 83cm plastic trash bags. The closed trash bags were thrown inside the bin and filling level data have been collected. The comparison shows that, the percentage of error reading is between 5-10% with some more fluctuation in several reading. It also shows that, the percentage of error is reduced as filling level is increased thus giving the opportunity to use this sensor with a motive to fulfil the goal of the proposed prototype.

The resistance AMS is used as Load Cell [21], which has a sensitivity of 2.0 ± 0.1 mv/V. Its accuracy grade is about 0.02% of full scale and resistant to weather. A 2300 mAh Li-ion rechargeable battery is used to supply power to the waspmote. The power consumption of all the sensors along with the mote and sensor board is shown in Table II. According to the data on Table II, the lifetime of the battery is around 65.55 hours if all the devices remain in active mode continuously. The level of battery left can be monitored by the waspmote.

TABLE VI
BIN CONDITION AND WASTE FILLING LEVEL SENSING AND WEIGHT MEASUREMENT DECISION FOR SEVERAL CASES

Case	Acceleration Change Detected	Proximity Value Measured	Time Threshold Exceed	Bin Condition			Filling Level Measured	Weight Measured
				Operative Situation	Lid Status	Loaded Status		
A	X and Y axis	1	No	Loading	Open	NOL	No	No
B	X and Y axis	0	No	Loading	Close	NOL	Yes	Yes
C	X and Y axis	1	Yes	Loading	Open	OL	No	Yes
D	X, Y and Z axis	0	No	Unloading	Close	NOL	No	No
E	X, Y and Z axis	1	Yes	Unloading	Open	ULC	No	No

The remaining battery value can be retrieved along with the sensor value in each active operation. The mote also can raise an alarm if the level reached to a certain threshold value as a warning. Battery replacement is easy in this design and as the battery is rechargeable, the system can spontaneously run with some backup battery. The costs of hardware used to develop the prototype considered reasonable. The purchase costs of each part of the system hardware are summarized in Table III. However the prototype may be cost-effective if commercially manufactured and a large quantity of components is purchased.

V. RESULTS AND DISCUSSION

Using the implemented prototypes, 55 test runs have been performed that completed 6 full cycles of loading and unloading of waste. In these test runs, all the possible combinations have been tested to check the bin functionality under different condition. The empirical outcomes shown in Table IV, represent the accelerations in three axis, the proximity sensor response, bin filling level values, weight of waste inside the bin and remaining battery power. In the lid status sensing system, once the drift and it's direction is detected based on the acceleration, the cover condition and operative situation is approximated to perceive the bin is overloaded or not towards different sensors activation. As the data shown in Table IV, when the bin is empty, it shows a value of less than 1 cm for filling level and 0 kg for weight. The test runs is performed considering different position of lid including small gap, normal gap, vertical position (rotating 90°, horizontal position (rotating 180°) and also for rotating the lid to an angle of 270° from its steady state position. During the loading operations, the bins position remains fix, only the lid positions are changed. The output of the accelerometer shows variation in three axes based on the lid positions. Table V presents acceleration data grouped by lid position. As shown in Table V, the fluctuations of acceleration data for the same configuration (like 'lid closed') occur due to the variation of lid position. During the unloading operation, the bins positions are changed that cause different patterns of acceleration data in this action. For experimental purpose, the bin is unloaded only when it becomes overloaded. The overloaded status is shown by a value of 9999 for waste filling. The remaining battery power shows an increasing trend in Table IV due to the fact that the battery is getting charged while the mote connected to computer for data collection. Based on the data of acceleration and lid proximity, the table shows the measurement of weight along with or without level value. The experimental data shows that the bin is successfully operated to show its status.

The 5 different cases of bin condition, waste filling level sensing and weight measurement decision is presented in Table VI under different condition. In the loaded status column, the terms NOL, OL and ULC are represented as not overloaded, overloaded and unload continue, respectively. The decision whether or not the weight sensing system is activated with or without the waste level sensing system is made using combination of distinct logic decisions on operative situation, lid status and time threshold. Thus, the merged verdict guides to the efficient and optimal execution of the implemented integrated system and validate the prototypes that can help to automate the solid waste management process.

VI. CONCLUSION

This work is a unique effort which incorporates accelerometer, magnetic proximity, ultrasonic and weight sensing methodologies respectively. The integrated sensing system is designed using rule-based decision procedure to offer a proficient and automatic bin status monitoring system. The crucial point is the algorithm which synthesize bin operative situation, its lid status, time threshold and loaded status perception. The functioning of the system is assessed by a number of tests run. The algorithms with the sensing systems have led to an intelligent bin which is very efficient for solid waste management automation.

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