Increasing efficiency of IoT-enabled waste collection with controlled mobility of robotic bins

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***Abstract*— Smart Cities cater for ever increasing population, which needs sustainable solutions for efficient wellbeing. Waste collection is significant for providing a green ecosystem in such cities. IoT-enabled waste collection solutions assist such a green ecosystem. Waste collection used to be performed by humans or via human intervention.However, contemporary research incorporates robots to perform waste collection. In this paper we describethe real case of a line following robot bin that assists waste collection in the Smart City of Saint Petersburg, Russia. Evaluation is performed through a model combining the distance covered by the actor, the time passed for the collection and the bins emptied. The results show the superiority of robot bins, compared to human workers, highlighting the impact of IoT-enabled robot assisted waste collection as part of a green ecosystem.**

Keywords—Smart Cities, IoT,waste collection, robot bins, optimization

I. INTRODUCTION

Smart Cities (SC) are evolving as the likely future of human habitation [1]. In such cities there is a need for intelligent applications to provide sustainable solutions for a variety of human living conditions. Smart environment is an area of interest for SCs. Specifically, efficient waste collection aims to reduce assets required and energy consumption towards a green ecosystem. Internet of Things (IoT) is an enabling technology towards this direction [2]. In the area of waste collection IoT has a key role to simplify and make processes effective and sustainable. In anIoT-enabled environment, dynamic scheduling and routing models for waste collection are extremely significant.

There is a variety of research focusing on human assisted waste collection [3]. However, humans follow a certain trajectory, driving waste trucks or mobile depots, to collect full of waste bins. Nowadays there is a trend to replace human factor with robot assisted waste collection.Approaches where robots are adopted to perform contemporary waste collection in SCs, in a variety of use cases,present the following characteristics: (1) they are eco-friendly, (2) focus on waste separation, (3) assist indoor waste collection, (4) perform coastal waste collection, and (5) work in a line following fashion. Robots used to collect waste have rather stand alone behavior mainly focusing on the task of collecting waste than to optimize the way waste is collected.

This paper proposes an efficient model to handle the waste collection process. The aim is to supportrobot assisted waste collection by replacing costly human intervention with cost efficient line following robot technology. The motivation is that in cases where bins are unreachable due to certain reasons, i.e., illegal parking, road labor, heavy traffic, narrow backyard, clusters of robots can commute waste collection more cost efficiently than humans with regards to time required and distance spent to collect waste in SCs. This is becausedynamic scheduling and routing are better applied to automated robot behavior than to unstable working human's trajectories.The obtained simulation results of using robot assisted waste collection in the context of SCs' green ecosystem,are promising.

The rest of the paper is structured as follows. In Section II it is presented related work in contemporary robot assisted waste collection. In Section III we analyzed the proposed optimized waste collection model. Experimental evaluation and discussion is presented in Section IV while Section V concludes the paper and suggests future work.

II. RELATED WORK

SCs provide a challenging IoT-based environment for performing contemporary research in the area of waste collection [4]. Dynamic scheduling and routing models for dealing with online waste collection requirements are presented in [5] whileadvances concerning efficient redesign and performance of waste collection processes by eco-friendly robots are reviewedin [6].

Specific applications of robotics in waste collection include, among many others, an intelligent waste sorting robotic arm system [7],a pick and place robot based on image processing for deterioration and non-deterioration waste separation [8],an amphibious robot network enhanced with crowdsourcingtechnology to perform waste collection on beaches, coastal locations and the oceans [9],a floating waste scooper robot to collect waste on water surface [10], and an implementationof beach waste collection robot [11]. Similarly, a fuzzy logic control system is utilized in an IoT-enable waste collection robot as presented in [12], while a wheeled robot in the SC of Peccioli performs robot-assisted tasks for door-to-door waste collection. The robot is able to navigate in the SC and interact with humans during the waste collection process [13]. Robot technology was also used to perform dynamic routing for waste collection after a physical disaster incident in SCs, as described in [14]

```
Main algorithm
Input: $incident$ //Reason for not physically reaching the bins
Output: $a$ //Actor performing waste collection, i.e., human, $h$, or
        //robot, $r$
        $optVal$ //Optimum value obtained by certain actor, $a$
Begin
While($True$)Do
    If(($incident ==$
        $unreachable\ bins\ due\ to\ illegal\ parking$) ∪
        ($incident == unreachable\ bins\ due\ to\ road\ labor$) ∪
        ($incident == unreachable\ bins\ due\ to\ heavy\ traffic$) ∪
        ($incident == unreachable\ bins\ due\ to\ narrow$
        $backyard$))then
        $\{d^h, t^h, b^h\} \leftarrow WasteCollection(h)$ //Returns distance, time,
                                                          //bins emptied by humans
        $\{d^r, t^r, b^r\} \leftarrow WasteCollection(r)$ //Returns distance, time,
        //bins emptied by robot bins
        $evalVal^h \leftarrow Evaluation(h)$ //Returns evaluated value
        //obtained by humans
        $evalVal^r \leftarrow Evaluation(r)$ //Returns evaluated value
        //obtained by robot bins
            $optVal^a \leftarrow Optimum(evalVal^h, evalVal^r)$
    End If
End While
End
```

Fig. 1. Main algorithm of the proposed model

```
Waste collection algorithm
Input: $a$ //Actor performing waste collection, i.e., human, $h$, or
       //robot, $r$
Output: $d^a, t^a, b^a$ //Distance covered, time required, bins
        //emptied during waste collection by certain actor, $a$
Begin
If ($a == h$)Then //Actor is human
    $\{d^a, t^a, b^a\} \leftarrow \boldsymbol{h.routing} \sim \{d.covered, t.spent, b.emptied\}$
        //Real data provided by human embodied sensors
        //according to human trajectory locomotion
        //from the Smart City of St. Petersburg, Russia.
else //Actor is robot
    $\{d^a, t^a, b^a\} \leftarrow \boldsymbol{r.routing} \sim \{d.covered, t.spent, b.emptied\}$
        //Synthetic data provided by robot embodied sensors
        //according to dynamic routing real trajectory as
        //described in [5]
End If
End
```

Fig. 2. Waste collection algorithm

Waste collection by robots in Smart Homes was also extensively researched. Matsuo*et al.*[15]performed an experimental evaluation of waste collection robot system for an indoor Smart Home kitchen. A semi-autonomous robot is designed and implemented for performing segregation to recyclable and non-recyclable waste in [16].An automated indoor waste collection system designed for Smart Homes is proposed in [17]. The system is based on a wave front model and the received signal strength indicator values to navigate the mobile robot. Finally, a robotdesign process decomposition is appliedin order to provide an automated solid waste collection system for SCs[18].

Ang*et al.* [19] presented an automated waste sorter incorporating a mobile line following waste root for efficient waste segregation and recycling to dumps and landfills. Similarly,a line following waste collection robot was also proposed by Jim *et al.* [20] to face the ever-increasing demand of contemporary SCs. In [21] it is proposed a line following robot system, which aims to replace vehicles for waste collection while a line following robot disposer designed for waste collection in airports, hospitals, schools and colleges is described in [22].Analysis of a line following robot, which was designed to collect waste from shopping centers is provided in [23].

The current work focuses on stand alone robot models to perform certain actions during the waste collection process. Theaim is to develop an effective model for cost efficient waste collection by incorporatingline following robot bins. The motivation, behind this idea, is to enable robot assisted waste collection in the SC of St. Petersburg in Russia to replace costly human intervention. In this context, cost is decomposed to time required and distance covered during waste collection process either by robots or by humans in real situations. Results highlighting the impact of IoT-enabled robot assisted waste collection as part of a green ecosystem, are also presented.

III. AN EFFICIENT WASTE COLLECTIONMODEL

Assume that a certain type of actor a, being either a human h or a line following robot bin r, performs waste collection in the SC of St. Petersburg in Russia. The proposed waste collection model decides which is the most effective way to collect waste from a certain actor a by obtaining an optimum value $optVal$,through the waste collection process. Let us define a set of reasons for, the waste truck, not being able to reach the bins. Such a reason is depicted in the system as an $incident$and takes one of the following forms: (1) illegal parking, (2) road labor, (3) heavy traffic, and (4) narrow backyard. In the case ofan$incident$the waste collection process is delivered by either a human h or a robot$r$. The output of waste collection process is modeled through a combination of the distance covered, the time required and the number of bins emptied either by h or by r. The output of waste collection process feeds the evaluation process, which is responsible to provide an $evalVal$ output evaluating the assigned waste collectionvalues, obtained by a certain type ofactor a.Subsequently, evaluation values, $evalVal$, of both actors h and r feed the optimization process, which is responsible to highlight the optimum value, $optVal$, for a certain actor a, thus infer which actor collects waste efficiently. The main algorithm of the proposed waste collection model is presented in pseudocode of Fig. 1.

```
Evaluation algorithm
Input: $a$ //Actor performing waste collection, i.e., human, $h$, or
        //robot, $r$
$d^a, t^a, b^a$ //Distance covered, time spent, bins emptied
                //during waste collection by certain actor, $a$
Output: $evalVal^a$ //Evaluated value obtained by certain actor, $a$
Begin
    If(($d^a == min$) ∩ ($t^a ==$ min ) ∩ ($b^a == max$))Then
        $evalVal^a \leftarrow max$ //Best case of waste collection by certain actor
    Else If (($d^a == max$) ∩ ($t^a ==$ max) ∩ ($b^a == min$))Then
        $evalVal^a \leftarrow min$ //Worse case of waste collection by certain actor
    Else
        $evalVal^a \leftarrow med$ //Average case of waste collection by certain actor
    End If
End
```

Fig. 3. Evaluation algorithm

```
Optimization algorithm
Input: $a$ //Actor performing waste collection, i.e., human, $h$, or
        //robot, $r$
$evalVal^a$ //Evaluated value obtained by certain actor, $a$
Output: $optVal^a$ //Optimum value obtained by certain actor, $a$
Begin
    If(($evalVal^a == max$) ∩ ($evalVal^{1-a} \in \{min, med\}$))Then
        $optVal^a \leftarrow max$ //Best case of waste collection by certain actor
    Else If (($evalVal^a == min$) ∩ ($evalVal^{1-a} \in \{med, max\}$))Then
        $optVal^a \leftarrow min$ //Worse case of waste collection by certain actor
    Else
        $optVal^a \leftarrow med$ //Average case of waste collection by certain actor
    End If
End
```

Fig. 4. Optimization algorithm

As already mentioned, in the main algorithm the model invokes the waste collection algorithm, which takes as input certain type of actor and provides as output the distance covered, time required, and number of bins emptied by that actor. In case the actor is a human h, then the routing process is performed by exploiting real data produced by human embodied sensors according to human trajectory locomotion provided by the municipality of the SC of St. Petersburg. In the opposite case where the actor is a line following robot bin r, data used for feeding the model are synthetic provided by robot-embodied sensors according to a dynamic real waste collection trajectory as described in [5]. The pseudocode of the waste collection algorithm is presented in Fig. 2.

The evaluation algorithm takes as input a type of actor (h or r) as well as the distance covered, the time required, and the number of bins emptied by that actor and provides as output the evaluated value $evalVal$. Incorporation of the evaluation algorithm in the model enables the characterization of waste collection process, i.e., $evalVal$, performed by certain actor as optimal, i.e.,max, average, i.e.,med, or bad, i.e., min. Specifically, if distanced covered is min, and time required is min, and number of bins collected is max, then $evalVal$ is characterized as max . In case thedistance covered ismax, and time required is max, and number of bins collected is min, then $evalVal$ is characterized as min. In any other case $evalVal$ for certain actor is characterized as med. The evaluation algorithm of the proposed model is presented in the pseudocode of Fig. 3.

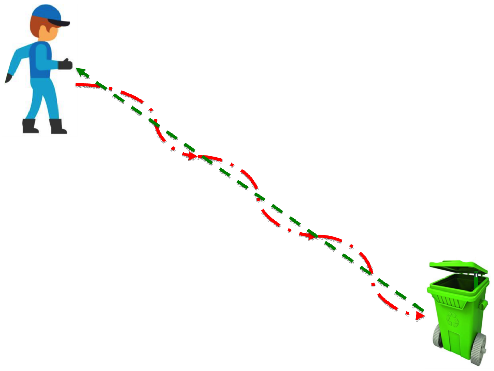

Fig. 5. Experimental environment

Whenever the model assigns certain $evalVal$ to each type of actor it is invoked the optimization algorithm, which takes as input both $evalVal$ of both actors and decides which actor performed better based on the outputs $optVal$.Intuitively, if $evalVal$ of actor a is max and $evalVal$ of the other actor, formally depicted as $1 - a$, is either min or med, then $optVal$ of actor a is max, which means that this is the best case of waste collection performed by actor a. In case $evalVal$ of actor a is min and $evalVal$ of the other actor is either med or max, then $optVal$ of actor a is min, which means that this is the worst case of waste collection performed by actor a. In any other case $optVal$ for certain actor has a med assignment. The optimization algorithm is presented in the pseudocode of Fig. 4.

IV. EXPERIMENTAL EVALUATION AND DISCUSSION

A. *Experimental Setup*

Consider an experimental environment where the bins are located in backyards of building blocks in St. Petersburg, Russia as shown in Fig. 5. There are two use cases to examine:In the first, the human actor $h$fetches the waste bin from the backyard to the waste truck, while in the second the line following robot bin $r$moves through a line painted on the floor from the backyard towards the waste truck and vise versa. It is expected that the h actor does not follow the shortest path between waste bin and waste truck due to locomotion error of human movement, while in the case of r actor it isfollowedthe shortest path for the same route. This means that time required and distance covered by line following robot bin r are more efficientcompared to that of human worker h.

TABLE I. EXPERIMENTAL PARAMETERS

Parameter	Value
Number of bins	[1,10] net number
Human average speed	$1.4\frac{meters}{second}$
Human distance covered	[29,247] meters
Human time required	[21.2,182.6]seconds
Robot average speed	$2.3\frac{meters}{second}$
Robot distance covered	[22,208] meters
Robot time required	[4.5,103.8] seconds

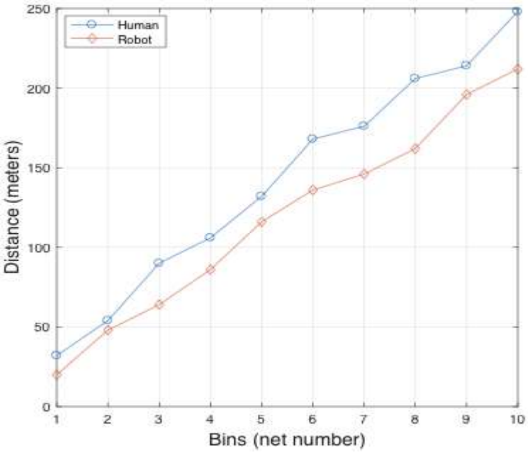

Fig. 6. Distance covered during waste collection

Experimental evaluation is performed by defining certain parameters as it can be seen inTable I. Specifically, we assume that a number of bins to get emptied range in$[1{,}10]$, the distance from bin to truck is 10 meters, thus fetching a bin to truck is in the best-case 20 meters. Line following robot bin $r$covers a distance in the range $[22{,}208]$ meters, since it follows a route computed by shortest path algorithm with minimum deviations from the effective distance defined. Instead, human worker $h$covers a distance in the range $[29{,}247]$ meters, since it is followed a human locomotion trajectory, which is prone to unexpected error deviations. Distance covered by human and robot bin is depicted in Fig. 6, where it canbe easily seen that robot performs better moving behavior during the waste collection process.

The average speed of human trajectory is assumed to be 1.4 m/s [24],while the average speed of line following robot bin, implemented by Arduino Engineering Kit, is assumed to be 2.3 m/s [25]. It is experimentally proved that time required to collect waste by robot bin is within range [4.5,103.8] seconds, while the corresponding time to collect waste by a human worker ranges in$[21.2{,}182.6]$ seconds (see Fig. 7).

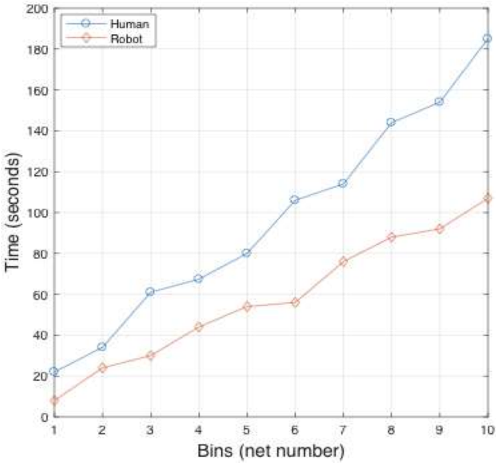

Fig. 7. Time required for waste collection

TABLE II. EFFICIENCY VALUE DECISION MATRIX

Actor	$optVal$		
	min	***Med***	***max***
h	++	0	--
r	--	**0**	++

B. Discussion on the Results

The efficiency value decision matrix, formed for by the experiments described in the previous section, is presented in Table II. We observe that in the case ofa human actor performs waste collection,$optVal$is in most casesmin. In contrary, in the case that the waste collection task is performed by a line following robot bin actor,$optVal max$ value is achieved in most cases. It is worth noting that $optVal$ for both actors h and $r$has zero med values, which means that robot bin is always better than human (or equivalently that human is always worse than robot bin) with regards to time required and distance covered during the waste collection process. Interpreting the results depicted in Table II, weeasily infer that the most efficient waste collection solution is observed in the case of line following robot bin. This is, mainly,becausethe robot bin covers shorter distanceas computed with the shortest path algorithm, while human trajectory is prone to spatiotemporal movement errors.

The authors recognize that additional metrics need to be taken into account, for instance, the cost of a robotic bin, energy consumption by the robotic bin and possibly condition of a human user who may need to carry a heavy load. In this series of experiments, we focused only on time passed and distance covered by each actor type.

V. CONCLUSIONS AND FUTURE WORK

Waste collection aims to transform urban environment to a green ecosystem. On this direction it is essential to redesign existing models of IoT-enabled services to meet the requirements of the SCs' era. In this paper we examined the case of aline following waste robot incorporated in the waste collection process. The waste collection task was accomplishedeither by a human or by a robot bin and we showed, experimentally, that a robot assisted waste collection is much more efficient compared to that of human assisted. The evaluation was performed on a combination ofthe time required to accomplish the task and the overall distance covered during waste collection.

In the future we aim to includeadditional metrics to gather more evidence on the superiority of robot assisted waste collection by incorporating and comparing methods to measure conditions of a human user who may need to carry a heavy load as well as electricity consumed by robots to perform certain routing trajectories. In addition, we aim to study how the robot is likely to react in case the line is not clearly marked on the ground surface due to a possible obstacle blocking the line. We also aim at adding more intelligence to the robotic bin to enable a degree of autonomy and obstacle avoidance.

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