Deterministic Static Sensor Node Placement in Wireless Sensor Network based on Territorial Predator Scent Marking Behavior

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***Abstract*:** An optimum sensor node placement mechanism for Wireless Sensor Network (WSN) is desirable in ensuring the location of sensor nodes that offers maximum coverage and connectivity with minimum energy consumption. This paper proposes a sensor node placement algorithm that utilizes a new biologically inspired optimization algorithm that imitates the behaviour of territorial predators in marking their territories with their odours known as Territorial Predator Scent Marking Algorithm (TPSMA). The main objectives considered in this paper are to achieve maximum coverage and minimum energy consumption with guaranteed connectivity. A simulation study has been carried out to compare the performance of the proposed algorithm implemented in two different single objective approaches with an Integer Linear Programming based algorithm and another biological inspired algorithm. The proposed single objective approaches of TPSMA studied in this paper are TPSMA with minimum energy and TPSMA with maximum coverage. Simulation results show that the WSN deployed using the proposed TPSMA sensor node placement algorithm is able to arrange the sensor nodes according to the objective required; TPSMA with maximum coverage offers the highest coverage ratio with fewer sensor nodes up to 100% coverage while TPSMA with minimum energy consumption utilized the lowest energy as low as around 4.85 Joules. Full connectivity is provisioned for all TPSMA approaches since the constraint of the optimization problem is to ensure the connectivity from all sensor nodes to the sink node.

***Keywords*:** deterministic, sensor node placement, Wireless Sensor Network, coverage, connectivity, energy, biological inspired

1. Introduction

One of the important problems in implementing a Wireless Sensor Network (WSN) is the position of the sensor nodes that will meet the design specifications such as coverage, connectivity and energy consumption. Coverage ensures the monitoring area is covered by at least one sensor node while connectivity is required to make sure that every sensor node is directly connected to the sink node or indirectly connected to the sink node via any other sensor nodes. Two sensor nodes that are outside the communication range of each other cannot communicate directly [1]. Consequently, connectivity cannot be guaranteed. Most applications in WSNs involve battery-powered nodes with limited energy where their batteries may not be convenient for recharging or replacing [2]. Thus, it is very crucial to find a way to reduce the energy consumption because it is inconvenient to keep on changing the battery especially if WSN is installed in remote areas. Once the sensor node is running out of energy, the data transmission will be interrupted hence the data needs to be retransmitted which causes delay and packets being dropped. Since the transmission distance also affects the energy consumption, it is another factor to be considered [3].

Due to these factors, a sensor node placement algorithm for WSN is needed to ensure that the position of deployed sensor nodes is able to provide maximum coverage, minimum energy without jeopardizing connectivity. Although the communication methods and protocols of the sensor node may affect the coverage, connectivity and energy consumption, they are only considered after the sensor node positions have been determined [4].

Romoozi [5] stated that there is a tradeoff between energy consumption and network coverage. Bigger coverage is achieved if the distance between two sensor nodes is further. However, their energy consumption will be higher due to longer distance data transmission. Coverage and connectivity can be optimized by deploying a large number of sensor nodes but the aim of this paper is to guarantee a full or almost full coverage and connectivity using fewer sensor nodes.

Sensor nodes can be deterministically or randomly deployed. Deterministic sensor node deployment is often necessary when sensors are expensive or when their operation is significantly affected by their locations. This is due to the fact that the desired coverage can be assured as the locations of sensor nodes are carefully planned according to certain requirements. On the other hand, random distribution of sensor nodes is suitable for harsh environment such as in battlefield, forest, disaster region and for environmental monitoring. However, the setbacks of random deployment are the desired coverage and accuracy might not be achievable [6]. The problem becomes more complex due to harsh environment and obstacle in the environment. Furthermore, randomly deployed sensor nodes may result in uneven density of sensor nodes where only certain area is having high density sensor nodes.

This paper introduces a deterministic sensor node placement algorithm for target monitoring by utilizing a new biologically inspired optimization algorithm known as Territorial Predator Scent Marking Algorithm (TPSMA). This algorithm imitates the behaviour of territorial predators in marking their territories with their odours. Two single objective optimization approaches are proposed here; TPSMA with minimum energy consumption and TPSMA with maximum coverage. Simulation results of the proposed algorithm are compared with an Integer Linear Programming (ILP) algorithm developed by Deyab et al. [7] and another biological inspired algorithm called Genetic Algorithm (GA). Some related works done by other researchers will be further discussed in Section 2. Our methodology is then presented in Section 3 followed by a simulation study in Section 4. Finally, based on the results obtained, a number of conclusions and recommendation for future work are drawn in Section 5.

2. Related Works

The scenario that has been discussed in the previous section has attracted numerous research works on WSN sensor node deployment. Abbasy et al. [8] compared the performance of sensor nodes placement strategies in terms of energy consumption. The strategies include random based and deterministic based deployment. The results show that random based sensor node placements consume more energy compared to deterministic based sensor nodes placement strategies. Deyab et al. [7] utilized an ILP to place sensor nodes for complete coverage of predetermined monitoring points. The aim of this work is to reduce the total cost of the sensor nodes. A deterministic sensor nodes placement method that considers coverage and connectivity based on grid scanning was proposed by Guo et al. [9]. In this method, target area is divided into square grids to denote the positions of targets and sensor nodes. Grid where the sensor node can cover the most target points and have the highest coverage level is selected to place the next sensor node. However, these sensor nodes may not be connected. Hence, they need to be rearranged and grouped with relay nodes in order to ensure the connectivity.

Most researchers nowadays prefer the Artificial Intelligence (AI) based approaches particularly those based on biological inspired algorithms in solving optimization problems in WSN [10-15]. This is because AI is proven to be able to give optimum solution for complex problems. Some of these algorithms are Intelligent Single Particle Optimizer (ISPO) [10], GA [11],[12], Optimized Artificial Fish Swarm Algorithm (OAFSA) [13] and the Glowworm Swarm Optimization Algorithm (GSO) [14]. Rahmani and Nematy [15] introduced an Evolutionary Approach based on Voronoi Diagram (EAVD) to place the sensor nodes. Static sensor nodes are randomly deployed then the area is divided into Voronoi cells. GA is then used to deploy additional mobile nodes in each cell to heal coverage holes.

Following section describes our TPSMA based sensor node placement algorithm with two different approaches namely TPSMA with minimum energy consumption and TPSMA with maximum coverage.

3. Methodology

This section elaborates the proposed method thoroughly beginning with a brief description on the territorial predator behaviour in marking the area. The following subsections will be focusing on the adoption of the biological behaviour into the sensor node placement algorithm with two different objective functions, the constraints and the problem formulation.

3.1. Territorial Predator Scent Marking Algorithm (TPSMA)

Territorial predators such as tigers, bears and dogs can be defined as predators that consistently defend a specific area against animals from other species. The territory is chosen based on certain factor such as food resources. Most territorial predators use scent marking to indicate the boundaries of their territories which are also playing a role in territorial maintenance and as information sites for other members of the population [16]. Chemical or olfactory communication enables these animals to leave messages that are relatively long lasting and can be read later by conspecifics. Furthermore, it can also be used at night, underground or in dense vegetation [16]. Animal odours can facilitate communication between conspecifics according to four different functions, scent matching, reproductive signalling, temporal or spatial signalling and resource protection [17]. Scent matching allows a resident animal to distinguish other residents from intruders by recognizing their scent, thereby reducing the need for territorial encounters [17]. The marks may be deposited by urination, defecation, rubbing parts of bodies such as chin and foot, scratching, using glands and vegetation flattening [16]. For example, to identify its territory, the male tiger marks trees by spraying of urine and anal gland secretions, as well as marking trails with scat. Dogs and other canines scent mark by urinating and defecation, while cats scent mark by rubbing their faces and flanks against objects. Bear rubs their bodies that have scent glands against the substrate. There are two phases in TPSMA known as Marking Phase and Matching Phase.

- Marking Phase

Predator checks on all food resources on L locations and marks the location with the highest food resource level, L_{marked}:

$$\forall x = \{1,2,...,L\} : (R_x \mid R_x \in [0,\infty)) \quad (1)$$

$$R_x = F(x) \quad (2)$$

$$L_{marked} = \max(R_x) \quad (3)$$

where

R_x = food resources level at location x
$F(x)$ = objective function value
L_{marked} = marked location

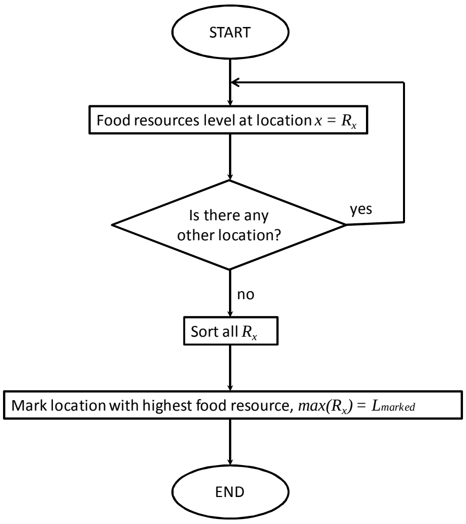
- Matching Phase:

Predator locates the marked location $L_{marked.}$ Assume that the predator locates L_{marked} based on Linear Search behaviour as shown in the algorithm below [18]:

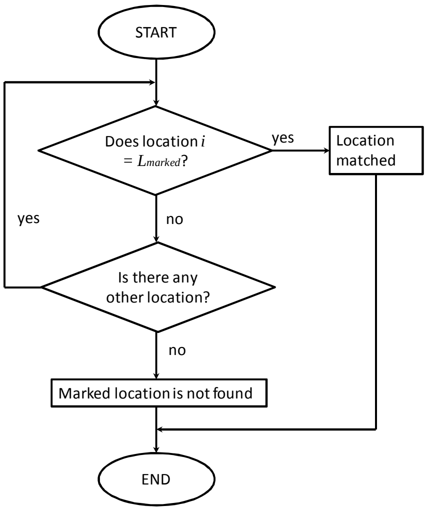
procedure *linear search* (L_{marked} : integer, R_1, R_2, ... ,R_L : distinct integers)
i:=1
while ($i \le L \wedge L_{marked} \ne R_i$)
i:=i+1
if $i \le L$

then *location* := *i*
else *location* := 0
return *location*

These phases are further illustrated in Figure 1(a) and Figure 1(b) respectively.



(a) Marking Phase



(b) Matching Phase

Figure 1. Process flow of TPSMA

3.2 TPSMA with Minimum Energy Consumption

The first objective is to minimize the energy consumption. Energy consumed by each sensor node, E_i can be determined as follows [19]:

$$E_i = E_{M_i} + E_{T_i} \times P_{iS} + E_{R_i} \times \alpha_i \tag{4}$$

where
E_M = Sensor node maintenance energy
E_T = Sensor node transmission energy
E_R = Sensor node reception energy
P_{iS} = Cost of minimum path from a sensor node *i* to the sink node
α_i = Number of sensor nodes from which the sensor node *i* receives data and transfer it to the sink node in multi-hop communication

Objective function, f_1 is the net energy consumed, *E*:

$$f_1 = E = \sum_{i \in S} E_i \tag{5}$$

3.3 TPSMA with Maximum Coverage

Coverage is expressed as a number of covered points function. Coverage for each monitoring point, $NCovered_p$ is determined as follows:

$$NCovered_p = \begin{cases} 1 & d(s_i, m_p) \le R \\ 0 & otherwise \end{cases} \tag{6}$$

where
R_s = sensing range
$d(s_i,m_p)$ = Euclidean distance between sensor node *i* and monitoring point *p*
The Euclidean distance can be calculated as follows:

$$d(s_i, m_p) = \sqrt{(x_{s_i} - x_{m_p})^2 + (y_{s_i} - y_{m_p})^2} \tag{7}$$

The objective function, f_2 is the sum of covered points, *NCovered*:

$$f_2 = NCovered = \sum_{p \in M} NCovered_p \tag{8}$$

where
M = total number of monitoring points

3.4 Constraints

There are two constraints of this optimization problem. First, the distance between any two sensor nodes must not exceed their R_C and there must be at least a path from the sensor node to the sink node to ensure connectivity. Only one sensor node can be placed in each monitoring location to limit the number of sensor nodes deployed. The monitoring locations are marked with *x(p)* as follows to indicate whether the location is equipped with a sensor node or not.

$$x(p) = \begin{cases} 1 & if\ location\ p\ has\ a\ sensor\ node \\ 0 & otherwise \end{cases} \tag{9}$$

$$const = \begin{cases} d(s_i, s_{i-1}) \le R_C, & i \in \{1,2,..., N\} \\ \alpha_i \ge 1, & i \in \{1,2,..., N\} \\ x(p) = 0, & p \in \{1,2,..., M\} \end{cases} \tag{10}$$

where

N = number of sensor nodes
M = number of monitoring points
R_C = communication range

3.5 Problem Formulation

A monitoring area is broken up into a number of small square tiles called monitoring locations. These monitoring locations are also the potential locations of sensor nodes. Thus, the number of monitoring locations is equal to the number of potential locations for sensor node. Each monitored location can only be equipped with one sensor node. The centre of each square tile is considered as the monitoring point and may be monitored by more than one sensor node. The area is obstacle free. Each sensor node has a specific initial energy and energy consumed by each sensor node affects the network lifetime because it is related to the working time of a sensor node. Energy consumed by the sensor node consists of three parts [19]:

- Maintenance energy: required for maintaining the sensor nodes in active state
- Reception energy: depends on the number of sensor nodes from which it receives data for transmitting to sink node
- Transmission energy: depends on the path in which the energy flows from the sensor node to the sink node

The problem is based on the assumptions listed in Lemma 1, 2 and 3 while the objectives are listed in Proposition 4 and 5. Problem 6 formalizes the optimization problem.

Lemma 1: The area is obstacle free; the sensing and communication ranges of all sensor nodes are identical and assumed to have a circular coverage area.

Lemma 2: Number of monitoring locations is equal to the number of sensor nodes potential locations.

$$M = P \tag{11}$$

where

P = number of sensor nodes potential locations

Lemma 3: Number of sensor nodes must not exceed the number of monitoring locations.

$$N \le M \tag{12}$$

Proposition 4: All sensor nodes should communicate with each other and there must be at least a path from the sensor node to the sink node to ensure connectivity as shown in equation (10).

Proposition 5: Monitoring points must be covered by at least one sensor node.

$$\forall p \in \{1,\dots,M\} \wedge \exists i \in \{1,\dots,N\}: \quad d(p,s_i) \le R_S \tag{13}$$

Problem 6: Place the sensor nodes that will give maximum coverage with minimum energy consumption with guaranteed connectivity. Each monitoring location can only be equipped with not more than one sensor node. The problem is represented by equations derived in subsections 3.2 and 3.3 subject to constraints in subsection 3.4.

3.6 Connectivity, Graph and Dijkstra's Algorithm

Dijkstra's algorithm [18] is used to check whether sensor nodes are connected to the sink node or not. Dijkstra's algorithm gives the minimum cost, P_{iS} and the number of hops, α_i between the sensor nodes and the sink node. A graph G is created containing all sensor nodes while an adjacency matrix is created which contains the sensor nodes that are connected. An edge (i, j) belongs to G if the distance between sensor nodes i and j is within the R_C. Dijkstra's shortest path algorithm is applied from each of the sensor nodes to the sink node. The output returned by the algorithm is the cost of the path, which is used to determine P_{iS} and the sequence of nodes in the path that will give α_i. Sengupta et al. [19] stated that graph theory is able to reduce the huge computational effort in formulating the objective functions.

4. Simulation Study

A numerical simulation has been carried out by using MATLAB and Network Simulator 2 (NS2) on Linux platform to demonstrate the performance and the effectiveness of the proposed algorithm based on recent studies.

4.1 Simulation Network Model

Figure 2 depicts the monitoring area with 60m x 60m dimension and consists of 144 equal width monitored locations. Sensor nodes properties are listed in Table 1.

1	2	3	4	5	6	7	8	9	10	11	12
13	14	15	16	17	18	19	20	21	22	23	24
25	26	27	28	29	30	31	32	33	34	35	36
37	38	39	40	41	42	43	44	45	46	47	48
49	50	51	52	53	54	55	56	57	58	59	60
61	62	63	64	65	66	67	68	69	70	71	72
73	74	75	76	77	78	79	80	81	82	83	84
85	86	87	88	89	90	91	92	93	94	95	96
97	98	99	100	101	102	103	104	105	106	107	108
109	110	111	112	113	114	115	116	117	118	119	120
121	122	123	124	125	126	127	128	129	130	131	132
133	134	135	136	137	138	139	140	141	142	143	144

Figure 2. Simulation network model

Table 1. Sensor nodes properties

Parameter	Value
Sensing range, R_S	15m
Communication range, R_C	15m
Initial energy	1Ah
Sensor node maintenance energy, E_M	13mA
Sensor node transmission energy, E_T	20mA/m
Sensor node reception energy, E_R	2mA

Figure 3 shows the convergence rate for TPSMA. It can be seen that the algorithm totally converged when the number of iterations reached 200. Thus, 200 iterations are considered in the simulation work.

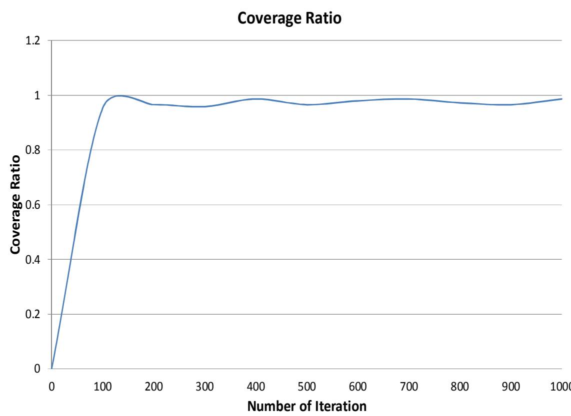


Figure 3. Convergence rate of TPSMA

4.2 Simulation Results

The WSN performance deployed with proposed sensor node placement algorithm is studied in terms of coverage ratio, connectivity probability and the average energy consumption. Simulation results of both TPSMA approaches are compared with results produced by an ILP based algorithm which is focusing on minimizing the cost proposed by Deyab et al. [7] and another biological inspired optimization algorithm known as GA as proposed in [11] and [12]. The simulation results of proposed algorithm are compared with these algorithms because they are recently studied and presenting the same network scenario.

Figure 4 shows the coverage ratio of WSN for different number of sensor nodes. As expected, the coverage ratio of WSN will increase as the number of sensor node increases. TPSMA with maximum coverage offers the highest coverage ratio with fewer sensor nodes compared to other algorithms. This is because the objective of this TPSMA is to achieve maximum coverage without considering any other criteria. In order to get at least 0.95 coverage ratio which represent the 95% threshold for coverage, TPSMA with maximum coverage needs less than ten sensor nodes compared to TPSMA with minimum energy consumption, Deyab's algorithm and GA which need around 20, 22 and 24 sensor nodes respectively. Furthermore, TPSMA with maximum coverage outperforms other algorithms by approximately 53% in terms of the deployment cost for 100% coverage since it requires the lowest number of sensor nodes.

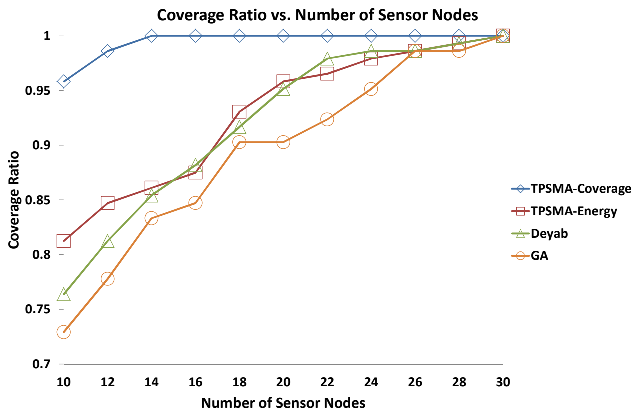


Figure 4. Coverage ratio

As depicted in Figure 5, all biological inspired based algorithms are able to provide full connectivity because these algorithms place the sensor nodes subject to full connectivity requirement as indicated by the constraints. On the other hand, Deyab's algorithm provides almost full connectivity when the number of sensor nodes is around 24 sensor nodes. As mentioned before, Deyab's algorithm is focusing on minimizing the deployment cost without considering any other criteria.

From the figure, it can be seen that the connectivity probability of Deyab's algorithm is unstable at the beginning. It reaches a steady state when the number of sensor nodes gives approximately 97% coverage. This is because, Deyab's algorithm places the sensor nodes randomly without any location constraint as required by TPSMA and GA.

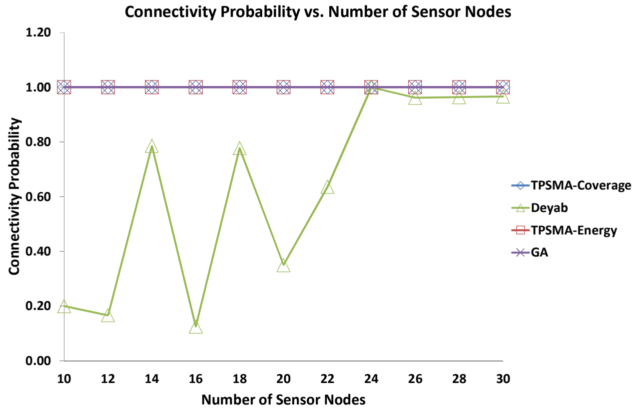


Figure 5. Connectivity probability

Figure 6 illustrates the average energy consumed by each sensor node when the minimum of 95% coverage is achieved. Constant Bit Rate (CBR) traffic is generated for the energy consumption measurement. The bar chart shows that, TPSMA with minimum energy consumption consumed the lowest energy compared to TPSMA with maximum coverage, Deyab's algorithm and GA approximately by 0.57 Joules, 1.34 Joules and 0.12 Joules respectively. This is due to the main objective of this TPSMA which is to place the sensor nodes at the location that gives the lowest energy usage without considering other criteria. On the other hand, Deyab's algorithm only considers the deployment cost and did not consider the energy factor. TPSMA with maximum coverage consumed more energy compared to GA because this algorithm only considers location with maximum coverage to place the sensor nodes without considering any other criteria. The result indicates that on average each sensor node of WSN deployed with both TPSMA with minimum energy consumption used considerably low energy which consequently will lengthen the sensor node's lifetime compared to other algorithms.

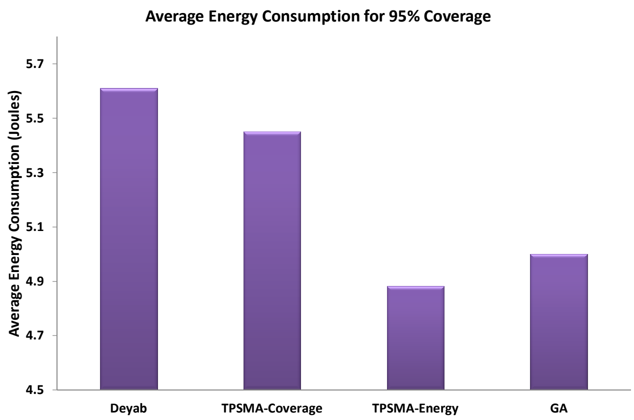


Figure 6. Average energy consumed by each sensor node for minimum of 95% coverage

5. Conclusion and Future Works

A biological inspired algorithm known as TPSMA has been developed in the paper to optimize the sensor node deterministic placement in a WSN. Two TPSMA approaches are presented in this paper known as TPSMA with maximum coverage and TPSMA with minimum energy consumption. A simulation study has been done to compare the performance of WSN deployed with the two different approaches of single objective TPSMA with an ILP based proposed by Deyab et al. [7] and GA. The simulation results show that as a whole, TPSMA with maximum coverage outperforms other algorithms in terms of coverage because the objective of this TPSMA approach is to get only maximum coverage. It differs with TPSMA with minimum energy which considers energy consumption to place the sensor nodes while Deyab's algorithm is only focusing on deployment cost. Full connectivity can be achieved with TPSMA and GA because the placement is done subject to full connectivity while Deyab's algorithm place the sensor nodes randomly without considering any connectivity factor. It can be seen that TPSMA with minimum energy consumption is able to reduce the energy consumption of the network as high as around 13% because the main objective of this TPSMA approach is to place the sensor nodes at the position that will consume lower energy compared.

Based on the study, it can be concluded that there is a tradeoff between the coverage and energy consumption affected by sensor nodes position. Thus, further work would be looking at developing a multi-objective sensor node placement algorithm that will consider both maximum coverage and minimum energy consumption without sacrificing the connectivity.

It is envisaged that the developed algorithm could be widely used in WSN applied for surveillance such as traffic monitoring and security as well as in precision agriculture such as for automatic irrigation system, fertilization and many more. With this enhancement, the overhead cost for both applications could be reduced while improving the quality of the product.

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