Provable Configuration Planning for Wireless Sensor Networks

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***Abstract*—Wireless Sensor Networks (WSNs) provide a flexible communication infrastructure for sensing and control. However, maintaining coverage is one of the most challenging tasks in configuring and deploying WSNs. Although there has been a significant amount research on providing coverage, most of the existing solutions focus on the coverage problem without giving attention to new sensing capabilities and dependability (security and reliability) requirements of WSN. Nevertheless, most of the existing techniques show limited scalability with the increasing number of sensors.**

In this paper, we present novel Satisfiability Modulo Theories (SMT) based formalizations to find the satisfying coverage configurations considering various practical security and reliability constraints. The presented approaches were implemented using Yices SMT Solver and evaluated extensively to show the feasibility and scalability of deploying our solutions in real-life WSN.

***Keywords*-Wireless Sensor Network; Network Management; Formal Methods; SMT;**

I. INTRODUCTION

Wireless Sensor Networks (WSNs) provide a flexible communication infrastructure for sensing and control in real-world applications. Examples of fields that utilize WSN include greenhouse asset management for climate control systems [1], [2]. Moreover, the new development in hardware miniaturization and wireless communication made the applications that involve large numbers of sensors possible. In many cases, wireless sensors are deployed in hostile terrain that make them hard to access. Therefore to provide coverage and accomplish the mission of WSN, it is important to obtain an efficient configuration planning that defines the status (active/dormant schedule) for the sensor nodes at the time of deployment. In addition, appropriate configuration planning is also important for energy saving. Coverage should be maintained during the lifetime of the WSN. On the other hand, WSN might have various security and reliability requirements in order to increase the dependability on WSN services. Therefore, the basic WSN coverage requirements are not sufficient as redundancy and variability in sensing tasks might be required in order to provide robustness and resiliency to WSN infrastructure. For example, WSN deployment may require sensor not to monitor the same point for sometime to guarantee stealthiness in the sensing process. Also, changing the sensing sources frequently for a specific monitored point increases agility of WSN against malicious attackers. Thus, due to limited battery power of sensors, it is important to have a configuration plan to maximize network lifetime under various security, reliability, and operational constraints.

In this paper, we show that configuration planning problems are computationally hard. We also define and formulate our configuration planning solutions to guarantee coverage for WSN using Satisfiability Modulo Theories (SMT). SMT is a powerful tool to solve constraint satisfaction problems arise in many diverse areas including software and hardware verification, type inference, extended static checking, test-case generation, scheduling, planning, graph problems, etc. [3]. An SMT instance is a formula in first-order logic with equalities involving uninterpreted functions (EUF) [4]–[6]. SMT solvers can determine the values of the Boolean variables that make a logic formula (with EUF) satisfying. Comparing with SAT, SMT provides a much richer modeling language using EUF [5], [7]. Yet modern SMT solvers can solve formulas with hundreds of thousands variables and millions of clauses [8].

Previous works on coverage planning for WSNs attempted to model the problem of maximizing WSN lifetime with coverage constraint as an optimization problem [9]–[12] and solved it using some heuristic algorithms. Many of the resulting systems, however, show limited scalability for $100s$ WSN nodes. In addition, most of the existing works focus on the coverage problem without giving special attention to dependability requirements or considering new constraints such as security constraints in configuration planning in WSN. Due to complexity of existing solutions, it may not look even feasible to include these constrains and new capabilities in the existing heuristics and still achieve good performance.

As shown in Figure 1, our approach formulates the coverage configuration planning problem as a constraint satisfaction problem using SMT. If the SMT instance can be satisfied, the satisfying assignment will provide the configuration planning. If the SMT instance cannot be satisfied, one need to relax the constraints or change input configurations such as number of sensors, sensor range, sensor lifetime or required network lifetime to find a satisfying solution.

The paper is organized as follows. Section II discusses the definition and the complexity of coverage configuration planning problem. Section III presents the SMT formalization of configuration planning constraints. Section IV presents eval-

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uation results. Section V presents related works. Section VI concludes the paper and proposes some future work.

II. COVERAGE CONFIGURATION PLANNING - PROBLEM DEFINITION AND COMPLEXITY

In this section, we will give more details about the problem and its complexity.

A. *Problem Definition*

One of the main objectives of coverage configuration planning is to extend the lifetime of the network (or maximize efficiency of energy use) while maintaining the required sensor coverage and other constraints. Sensors have limited sensing radius, which means only the locations or events inside the sensing radius can be sensed or detected. For point coverage, a specific sensor can only cover those points that are in its sensing radius. To maximize the lifetime of the WSN, the sensors can be awake in different time intervals while maintaining coverage at every interval. For example, as shown in Figure 2, we have 12 sensors which can monitor four points in the figure. Sensors $s_{3*(i-1)+1}$,$s_{3*(i-1)+2}$, and $s_{3*(i-1)+3}$ cover point i ($1 \leq i \leq 4$), and every sensor is awake in one of three consecutive time intervals. We can see that in this schedule, all monitored points will be covered in every time interval.

In addition to the coverage requirement, we may have the following constraints for different applications:

- *Redundancy constraint.* In some WSN applications, it is required that every point should be covered by at least K sensors at any time [13]. This can improve the reliability of the WSN.
- *Evasive constraint.* If the sensors are deployed in a hostile terrain [14], [15] or are used to monitor critical infrastructures [16], it is important to protect the sensors from being detected by adversaries. This usually performed by adding constraints to enforce every sensor to not to be in an active sensing status for more than K_1 time intervals.
- *Moving Target constraint.* To improve resiliency and security, we may require that some critical points should not be covered by the same sensor in more than K_2 time intervals. Having this constraint will make it more difficult for an adversary to attack selected sensors that cover the critical points because the sensors that cover a critical point are rotating and not fixed to a specific set.
- *Partial coverage constraint.* In some applications, we may only need partial coverage [17], [18]. For example, we may require that every point to be covered by at least T_1 out of the T ($T_1 < T$) time intervals, or only require m_1 out of the m ($m_1 < m$) points to be covered at every interval.

B. *Complexity*

The problem of maximizing WSN lifetime with the basic coverage requirements can be formalized as a maximum Disjoint Set Cover (DSC) problem [10].

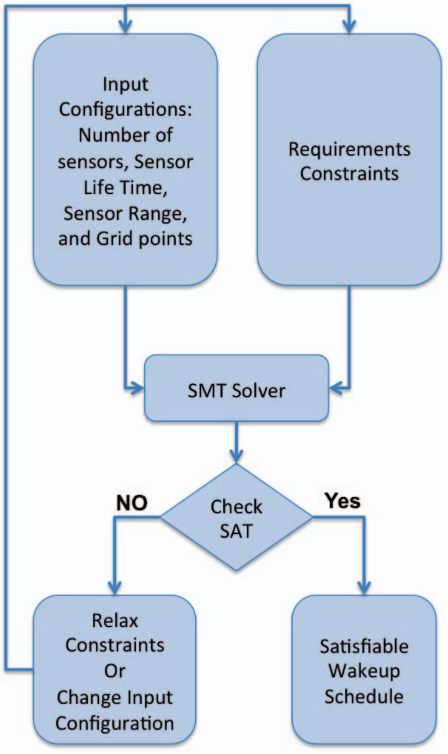

Fig. 1. Overview of the Problem

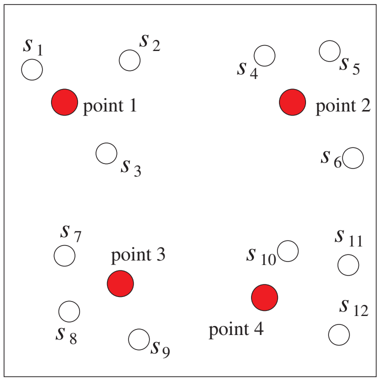

Fig. 2. An example of point coverage planning

Definition 1: Suppose there is a set $P = \{p_1, p_2, \ldots, p_m\}$ and a collection $\mathcal{C}$ of n sets (correspond to sensors in the language of WSN) $s_1, s_2, \ldots, s_n$, where $s_i \subseteq P$ ($1 \leq i \leq n$), Given a number T, can one divide the n sets $s_1, s_2, \ldots, s_n$ into T disjoint partitions $\mathcal{C}_1, \mathcal{C}_2, \ldots, \mathcal{C}_T$ such that every partition covers all elements in P? Here a partition $\mathcal{C}_i$ ($1 \leq i \leq T$) covers all elements in P means $\bigcup\limits_{s \in \mathcal{C}_i} s = P$.

In this definition, we can consider the set $P = \{p_1, p_2, \ldots, p_m\}$ as the set of monitored points, and the n sets $s_1, s_2, \ldots, s_n$ as n sensors, where every sensor covers a subset of P. In the definition, every sensor is assumed to have a lifetime of one time interval. If a sensor has a lifetime of multiple time intervals, we can duplicate it as multiple

TABLE I

A GLOSSARY OF THE VARIABLES USED IN THE MODEL

Name	**Type**	**Discription**
n	Integer	Number of sensors.
m	Integer	Number of monitored points.
T	Integer	Life time of the network.
s_i	Integer	The i^{th} sensor.
w_{ij}	Boolean	Decision variable to indicate the status of the i^{th} sensor at the j^{th} time slot.
L_i	Integer	Sensor's life time.
r	Integer	Sensor's range.
S	Set	The set of all sensors.
P	Set	The set of all monitored points.
P_1	Set	The set of all critical points.
U_i	Set	The subset of monitored points covered by the i^{th} sensor.
σ_j	Boolean	Decision variable used in partial time coverage.
σ_k	Boolean	Decision variable used in partial space coverage
K	Integer	Threshold to specify the minimum number of sensors to cover each point at any time interval.
K_1	Integer	Threshold to specify the count of consecutive time intervals in the *evasive constraint*
K_2	Integer	Threshold to specify the count of consecutive time intervals in the *moving target constraint*

sensors with lifetime of one time interval. The problem was first proved to be NP-complete in [10], but no approximation algorithm is known.

III. SMT FORMALIZATION FOR COVERAGE CONFIGURATION PLANNING

Suppose there are n sensors $S = \{s_1, s_2, \ldots, s_n\}$ and m monitored points $P = \{p_1, p_2, \ldots, p_m\}$. Sensor s_i covers a subset U_i of points in P. Assuming sensor s_i has a lifetime of L_i time intervals, we need to make a plan to make the coverage lifetime of the WSN for T time units. Sensor's lifetime, L_i, is a generic estimation which is equal for all sensor nodes. Table I lists all variables used in our model.

Now we will discuss modeling and formalization of the constraints. For basic point coverage where at every interval, every monitored point should be covered by at least K sensors, we can formulate the configuration planning problem as the following SMT instance:

$$\sum_{1 \le j \le T} w_{ij} \le L_i,\ 1 \le i \le n \tag{1}$$

$$\sum_{i \in \{i | p_k \in U_i\}} w_{ij} \ge K,\ 1 \le k \le m, 1 \le j \le T \tag{2}$$

$$w_{ij} \in \{0, 1\}, 1 \le i \le n, 1 \le j \le T. \tag{3}$$

The variable w_{ij} ($1 \le i \le n$, $1 \le j \le T$) is the indicator of the status of sensor s_i at time interval j. $w_{ij} = 1$ means sensor s_i is awake at time interval j, and $w_{ij} = 0$ means otherwise. The first constraint requires that the lifetime of every sensor is at most L_i time intervals, and the second constraint requires that every monitored point should be covered by at least K sensors in every time interval. The last constraint sets the bound for variables w_{ij}.

Note that all the above constraints are in linear format, so the formalization can also be solved by ILP (Integer Linear Programming). But we need to combine these constraints with other Boolean or arithmetic constraints of configuration planning. SMT provides the most suitable formulation environment for this problem.

For the evasive constraint, we add the following constraint into the SMT formulation:

$$\sum_{j=l}^{l+K_1} w_{ij} \le K_1,\ 1 \le i \le n, 1 \le l \le T - K_1 \tag{4}$$

This basically means that during all time intervals, a sensor will not be in a sensing status more than K_1 consecutive intervals. Eq. 4

For the moving target constraint, suppose the set of critical points is P_1 ($P_1 \subseteq P$), we add the following constraint into the SMT formulation:

$$\sum_{j=l}^{l+K_2} w_{ij} \le K_2,\ \forall i \in \{i | U_i \cap P_1 \neq \Phi\}, 1 \le l \le T - K_2 \tag{5}$$

Here Φ is the empty set.

For the partial time coverage where every point is to be covered by at least T_1 out of the T ($T_1 < T$) intervals, we replace Eq. 2 with the following constraints:

$$(\sigma_j = 1) \Leftrightarrow \left(\bigwedge_{1 \le k \le m} \sum_{i \in \{i | k \in U_i\}} w_{ij} \ge 1 \right),\ 1 \le j \le T \tag{6}$$

$$\sum_{1 \le j \le T} \sigma_j \ge T_1 \tag{7}$$

$$\sigma_j \in \{0, 1\}, 1 \le j \le T \tag{8}$$

For the partial space coverage where only m_1 out of the m points are to be covered in every interval, we replace Eq. 2 with the following constraints:

$$(\sigma_k = 1) \Leftrightarrow \left(\bigwedge_{1 \le j \le T} \sum_{i \in \{i | k \in U_i\}} w_{ij} \ge 1 \right),\ 1 \le k \le m \tag{9}$$

$$\sum_{1 \le k \le m} \sigma_k \ge m_1 \tag{10}$$

$$\sigma_k \in \{0, 1\}, 1 \le k \le m \tag{11}$$

As shown in Figure 1, the previous constraints and input configurations (number of sensors, number of points, sensor's lifetime, WSN's lifetime and sensor's range) are fed to the SMT solver to find a satisfiable configuration plan that gives the wakeup schedule of all sensors used in the WSN.

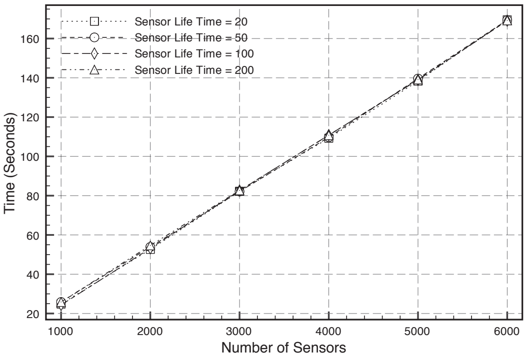

Fig. 3. The effect of changing sensor lifetime (L_i) on running time. (5*5 cells grid, r = 100m, T= 300).

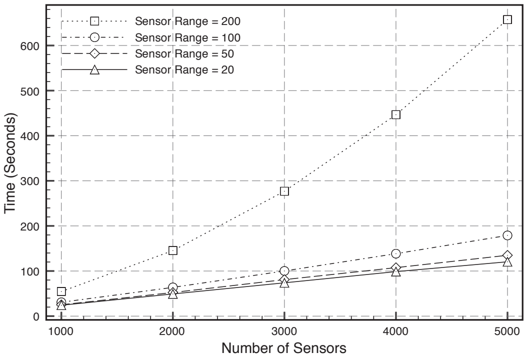

Fig. 4. The effect of changing sensor range (r) on running time. (10*10 cells grid, L_i = 100, T= 300).

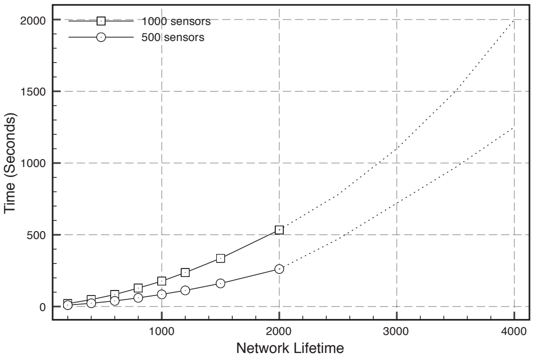

Fig. 5. The effect of changing network lifetime (T) on running time. (6*6 cells grid, L_i = 0.25*T, r= 200m).

IV. IMPLEMENTATION AND EVALUATION

In this section we will describe the implementation details and evaluation settings used to generate and simulate wireless sensor networks. Also, we will show and discuss our evaluation of the performance results for the configuration planning solutions described in the previous sections.

All evaluation results were simulated on 1.33 GHz dual core CPU with 3 GB memory. All formulas discussed in this paper are implemented in C++ language (650 lines of code) and Yices API SMT solver [19]. The scalability of our approach is shown by the ability to find configuration plans for thousands of sensors.

The main goal of this evaluation is to measure the impact of critical parameters such as number of sensors, sensor range, network lifetime, and partial coverage on the time required to obtain a satisfying configuration for point coverage. The second goal is to investigate the UNSAT and failure to obtain an answer by the SMT solver under various parameter values.

A. Evaluation methodology

In our evaluation for the proposed formulas, we generate a network grid of 1000 meters by 1000 meters. The grid is divided into equal l^2 cells. At each grid point there is a monitored point to be covered. Setting cell size to 250mx250m we get 5x5=25 points, while setting cell size to 100 gives 11x11=121 points. Although, we used fixed area the critical parameters (eg. number of sensors) can still be randomly selected. We assume that a sensor can cover all points in its range. The following random parameters are used in the evaluation: number of sensors (n), number of points to be covered (m), network lifetime (T), sensor lifetime (L_i) and sensor range (r). Changing the previous parameters ensures the randomness and the variance in WSN topologies. The comprehensiveness of input parameters covers wide ranges of different WSN deployment algorithms. All sensors in all experiments are allocated randomly using uniform distribution. Each experiment is repeated 10 times and the average is reported.

B. Evaluation Results

In this section, we show the effect of sensor lifetime, sensor range, network lifetime, redundancy constraint, evasive constraint, moving target constraint, and partial coverage constraint on running time for coverage planning.

Impact of Sensor Lifetime (L_i): Sensor lifetime plays an important role in configuration planning. Eq. 1 ensures that a sensor can not be scheduled more than its life time. Figure 3 shows the effect of changing sensor lifetime L_i on running time. This shows that running time is not affected by changing the sensor lifetime. The linear trend in Figure 3 reflects the scalability for finding a plan for large number of sensors. In the case of failure to find a satisfying plan, sensor lifetime can be changed and given back to the SMT solver as shown in Figure 1. Rechecking the satisfiability by changing sensor lifetime adds no overhead on the original problem.

Impact of Sensor Range (r): Figure 4 shows the effect of changing sensor range (r) on running time. Increasing sensor range allows more points to be covered for each sensor. When number of sensors covering a single point increases, more time is needed to find a satisfying schedule for all sensors to cover the entire period of time T. From Figure 4, sensors with range less than 100m shows linear increase on time overhead. While

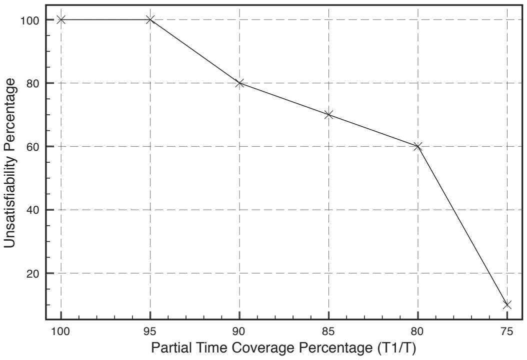

Fig. 6. The effect of Partial time coverage constraint. (5*5 cells grid,n=100, L_i = 10, T=200, r= 100m)

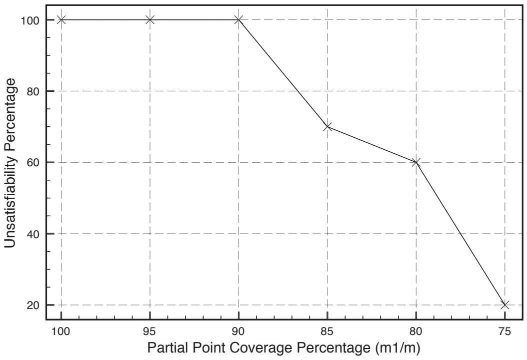

Fig. 7. The effect of Partial point coverage constraint. (5*5 cells grid,n=100, L_i = 10, T=200, r= 100m)

the quadratic trend appears for sensor range = 200m. In both cases, the scalability for large number of sensor still in the practical limits. For instance, finding a satisfying configuration plan for 5000 sensors with range of 200m takes 650 seconds in average.

Impact of WSN Lifetime (T): WSN lifetime is the spanning operational age for a WSN. Figure 5 shows the effect of changing network lifetime T on running time. Increasing network lifetime will increase the problem space. Larger T values means more time units are needed to be checked and configured for finding a satisfying plan. Figure 5 shows that the running time to find a satisfying assignment increases quadratically with the network lifetime. From Figure 5, finding a satisfying plan for 1000 sensors in 2000 interval units WSN lifetime takes 520 seconds in average. For the cases that the required network lifetime (T) is more than 2000, Yices solver cannot solve the problem due to insufficient memory space (the machine we use has 3G RAM). We extrapolate the running time for $T > 2000$ to show the quadratic trend in the figure.

Impact of Asserting Partial Coverage Constraint: In some cases, SMT solver is unable to find a satisfying configuration plan for the sensors. As shown in Figure 1, constraint relaxation may provide a satisfying plan. Equations 6-11 introduce two types of constraint relaxations: partial time constraint and and partial point constraint. Figures 6 and 7 show how partial time constraint and partial point constraint can help in finding a satisfying configuration plan. Decreasing the partial time/point percentage has a noticeable effect on decreasing the unsatisfying planning percentage. In Figure 6, decreasing partial time coverage percentage to 75% reduces the unsatisfiability percentage to 10%.

To the best of our knowledge, the most closest work to our work is the work presented in [10]. In this work, the basic point coverage is evaluated using less than 100 sensors and 100 monitored points. In other works [9], [11], [12], the number of sensors used is less than 1000. It is hard to make a comparison with other works. However, this work is the first to show configuration planning with such large number sensors and other flexible parameters.

V. RELATED WORKS

The survey papers [20], [21] gave a broad overview of the work that had been done to address the coverage problems in wireless sensor networks. Cardei. et al. proved the hardness of disjoint set cover problem and presented some heuristic and linear programming based algorithms in [10]. K-coverage in WSNs was discussed in [13], where the authors presented polynomial-time algorithms, in terms of the number of sensors, to verify the K-coverage of the monitored region. Shu et al. investigated the maximization of the coverage time for a clustered wireless sensor network (WSN) by optimal balancing of power consumption among cluster heads in [11]. The work in [22] addressed the problem of minimizing power consumption in each sensor node locally while ensuring global communication connectivity and coverage. Algorithms for three-dimensional sensor coverage were presented in [12], [23]. Coverage problems in wireless ad-hoc sensor networks were discussed in [24]. In [25], the authors considered the problem of designing control protocols for PTZ cameras within a smart camera network where the goal was to guarantee certain temporal logic specifications related to a given surveillance task. This approach can be extended naturally to WSNs with mobile sensors. The work in [26] described an incremental deployment algorithm for mobile sensor networks to maintain coverage and other constraints. The work in [27] designed and evaluated distributed self-deployment protocols for mobile sensors to eliminate coverage holes. In [9], the authors presented a node-scheduling scheme for WSNs to can reduce system overall energy consumption, therefore increasing system lifetime, by turning off some redundant nodes. The major technique in this approach are coverage-based off-duty eligibility rule and backoff-based node scheduling scheme which can guarantee that the original sensing coverage is maintained after turning off redundant nodes. In [28], the authors studied efficient triangular grid-based sensor deployment planning for coverage and discussed several approaches to efficient grid-based deployment planning for coverage and illustrate these through numerical examples. The work done in [29] studied the problem of network design in heterogeneous WSNs that involves optimization of network costs associated with different classes of nodes versus maximizing coverage and network lifetime. The work done in [30] presented some location dependent heuristics for sensor coverage deployment planning. Probabilistic sensor coverage was discussed in [31], [32]. While all the above mentioned works addresses various coverage related problems and algorithms, our approach in this paper provides a general SMT based framework for coverage configuration planning that can be flexibly combined with different constraints.

VI. CONCLUSION AND FUTURE WORK

Wireless Sensor Networks (WSNs) present a great capabilities to be used in real-word applications. One of the important issues in WSNs is the coverage planning. In this paper we define the configuration planning problems for WSNs by including new sensing capabilities and dependability (security and reliability) requirements of WSN. We show the problems are hard to solve and present SMT based formalizations that can be combined with various security, reliability, and operational constraints. We evaluated the formalizations for WSNs with number of sensors up to 6000. The evaluation shows the feasibility and scalability to solve the coverage configuration planning problem using SMT based formalizations. In the future, we plan to extend the SMT based approach to probabilistic coverage verification and planning and to formalize coverage constraints for multi-point and multi-position/multi-direction sensors.

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