Application of Radio Frequency Identification Devices to Support Navigation of Autonomous Mobile Robots

Olaf Kubitz, Matthias O. Berger, Marcus Perlick, René Dumoulin
Informatik 4 (Communication Systems) and European Centre for Mechatronics
RWTH Aachen, 52056 Aachen, Germany
E-mail: {kubitz,berger,perlick,dumoulin}@i4.informatik.rwth-aachen.de

***Abstract*— Autonomous mobile robots are expected to be a solution for a vast of applications in service and industry applications. However, a great and still unsolved problem for most environments and applications is the robust and cheap positioning, i.e. the determination of the robot's current position. In this paper a navigation system is presented, that is based on the use of radio frequency identification (RFID) as artificial landmark system. In combination with the presented behavior based control architecture this system enables the robot to reach any reachable landmark in its environment through a topological robot positioning approach. A technique called re-classification (which depends on the special features and advantages of RFID systems) is presented that makes it possible to determine the robot's exact global position in presence of a landmark. Based on this accurate position (i.e. its coordinates) the robot can reach an arbitrary goal specified by coordinates even if it is not marked with a RFID landmark.**

I. Introduction

Autonomous mobile robots are expected to be a solution for a vast of applications ranging from service robots, e.g. in hospitals, over cleaning robots, e.g. at airports or railway stations to industrial applications. The aim of our research project is to operate and navigate a mobile robot in industrial and business environments in order to solve transportation tasks. A great and still unsolved problem for most environments and applications is the robust and cheap positioning, i.e. the secure and unique determination of the robot's current position. Especially industrial applications of autonomous mobile robots have a strong need for easy, robust, and cheap navigation aids. The lack of appropriate positioning systems still prevents mobile robotics from broad usage in most indoor environments.

II. Positioning Systems in Mobile Robotics

The existing solutions for autonomous mobile robot positioning can be divided into two categories [1]:

- Absolute position measurements
- Relative position measurements

The work of M. O. Berger and Olaf Kubitz is supported by the Deutsche Forschungsgemeinschaft, Graduiertenkolleg 'Methods and tools of computer science and their application in technical systems', grant no. Sp 230/6–6. Cooperation and support by the European Center for Mechatronics, Prof. Drews in Aachen is gratefully acknowledged.

Absolute position measurements (e.g. using active and passive beacons or landmarks) generally provide a good estimation of the robot's location but in most cases they depend on expensive and costly infrastructure preparations. These are the installation of beacons or major changes in the environment to adapt it to the robot's needs. For example positioning systems based on radio frequency (RF) phase measurements have limitations as they are not reliably usable in buildings with several rooms and thick walls of concrete due to distortions and multi-path reflections of electro-magnetic waves.

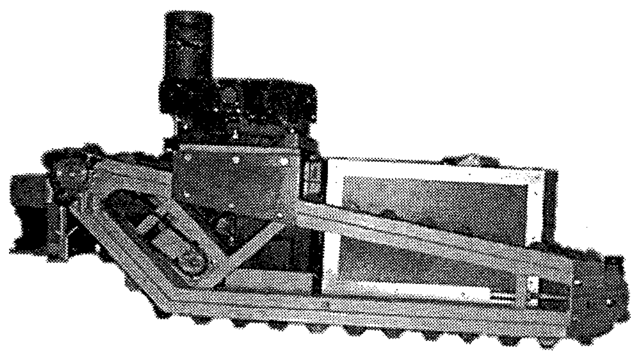

Figure 1: The mobile target platform at European Centre for Mechatronics [2] used for the experiments.

In contrast, relative position measurements (e.g. inertial navigation or odometry) are self-contained and do not have to rely on external equipment. A typical example is dead reckoning that is well known for providing a good short-term accuracy, being inexpensive, and allowing very high sampling rates. However, the fundamental idea of dead reckoning is the integration of incremental motion information over time. The fact, that motion information, i.e. the current direction and length of the path traveled since the last measuring cannot be measured precisely leads inevitably to the accumulation of errors. Particularly, the accumulation of orientation errors will cause large position errors which increase unbounded with the distance traveled by the robot.

III. Map based positioning

Map based positioning is a well known technique based on the process of map-matching. It is widely used in mobile robot positioning. To determine its global position the robot uses its sensors like ultrasonic or laser range measuring systems [3, 4] to build a temporary map of its local environment. Then the global map previously stored in the robots memory is searched for matches with the local map. The robot's global

0-7803-3659-3/97 $10.00 ©1997 IEEE

position is then computed by applying the transformation that matches the local to the global map to the robot's local position.

Map-based positioning has several disadvantages which can be easily eliminated by the use of RFID as explained below.

- The probability of mismatch is relatively high. Furthermore, dynamic environments and noisy sensor signals rise the probability of mismatching.
- In order to form geometric primitives sensor readings have to be grouped to make map-matching possible.
- Especially in typical indoor environments the local map can often be matched to several places in the global map. So, even after matches are established the computed position of the robot has still a certain amount (strongly dependent on the current environment) of probable inaccuracy.
- The widely proposed use of dead reckoning to support the map-matching process implies the need of a very realistic model for odometry (e.g. see [5]) which itself provides good accuracy only in short terms.
- As the matching of two arbitrary maps is a challenging problem, much computing-time is needed to process the match.

IV. Radio Frequency Identification (RFID) Systems

RFID stands for radio frequency identification. It is based on magnetic, radio or electro-magnetic propagation and allows the wireless identification of RFID tags. A typical system consists of an interrogator/reader that communicates wireless with a number of tags. Different systems provide the detection of the presence of tags, their unique identification or even read/write access to the tag's internal memory. The use of electro-magnetic propagation allows the energy to penetrate certain materials and therefore to access tags that are not visible.

A. How RFID Systems work

There exist two main methods to provide the RFID tag with energy for the communication and for an internal processor that might be integrated in tags. Either an internal long-life battery powers the transceiver or energy from the interrogator is transmitted to the tag as follows.

The energizing field is emitted from the transmitter in the interrogator in the form of a carrier wave signal at a fixed frequency. This energy from the transmitter is collected by the transponder antenna, rectified and used to power the transponder. The transponder generates a data stream comprising a clock signal and the data to be communicated is a form of a modified manchester code.

The data from the transponder is used to drive a shorting transistor across the antenna, which has the effect of changing the reflectivity of the transponder antenna and causing some of the received energy from the transmitter to be reflected back towards the receiver. This reflected energy has the form of packets of energy at a frequency that is shifted from the original transmitter carrier by the clockrate of the transponder. A simple receiver in the interrogator using the transmitter signal as a local oscillator can decode the received energy and extract the modified manchester code.

B. RFID Systems and Mobile Robotic

Our approach uses RFID for position determination of a robot. Radio frequency identification cards are used as a means to support the robot's navigation by placing tags (i.e. the cards) as artificial landmarks within the environment. The idea is to install an interrogator on the moving robot and to detect, read and modify the data on identification cards attached to walls, containers, machines or other specific places in the environment as soon as the robot moves along.

By this, the robot is able to detect items, places or other robots and update its position and maps accordingly. The information (e.g. an ID) stored in the card in combination with some kind of map will give the robot revelation of its own position or can even be used to update the inaccurate dead reckoned position. However, infrastructural preparations are needed but they are very easy and cheap. The cheap RFID tags are located at any position where an landmark is required.

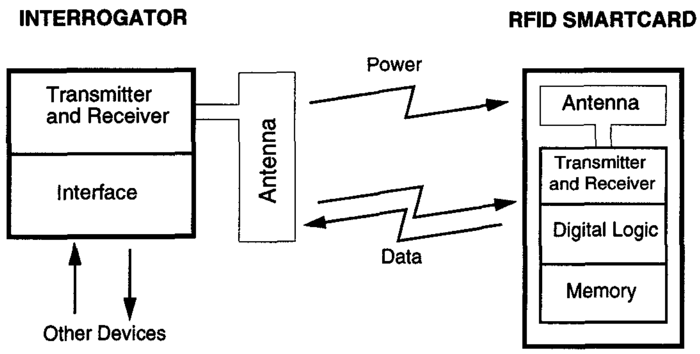

Figure 2: RFID System: Interrogator Communication with RFID tag

We investigate a typical RFID system [1] working with up to 100 channels in the 2.45 GHz range. The transmission range is up to 4m with a reading rate up to 16 kbit/s and a writing rate of 4 kbit/s. Some systems allow the detection of approaching or moving away and the relative speed between tag and interrogator which yields to a more accurate estimated position of the robot. The ID-badges are factory marked with an 8 digit unique code and provide additional 606 bits memory, e.g. for 82 digits (7 bit) with encryption and 32 bit checksum for data. A number of systems allow several tags to be read at a moment, allowing multiple tags to be distinguished simultaneously.

V. Behavior based architecture

The behavior based control architecture used on our robot is especially designed to be able to integrate several positioning sensors with different accuracies and error categories while enabling the robot to navigate in industry and office environments. The control architecture [6] mainly consists of three parts.

In the first part run several behaviors systems that generate commands for the actuators from sensor inputs [7, 8, 9]. The second part receives commands from the active behavior systems and generates (e.g. by superposition or subsumption)

[1] Support by Pepperl+Fuchs, Germany, is thankfully acknowledged

orthogonal commands for the actuators. These two parts enable the robot to wander around while avoiding obstacles as well as to approach a goal as far as possible due to sensor noise and dead reckoning errors. In the third part internal feedback within the robot's control architecture is achieved through an entity serving as a virtual actuator as well as a virtual sensor. This entity manages the system's internal states. The modeling of more complex behaviors like 'follow a wall', 'minimize distance to position (x, y, z)', 'turn to heading $x°$', and so on, is based on internal states. The stimulation of certain complex behaviors is done by a current abstract navigational command called the *objective.* The objectives help behaviors to decide on their intended actions. For example, a robot approaching a wall with the current objective set to 'general direction is left' will turn left if there is enough free space.

These three parts together on the one hand enable the robot to navigate locally in an environment, avoiding obstacles and on the other hand allow the global navigation towards a goal without explicit geometric knowledge of the entire environment. This paper will focus on the use of RFID as a means to globally navigate a robot with this behavior based architecture. Please note, that the RFID based navigation itself is behavior-based, i.e. it is integrated in behavior systems.

VI. RFID Tags as Landmarks

In our approach, RFID tags are used as artificial landmarks in the robot's environment. The robot is able to uniquely identify the tags by the on-board interrogator. Hereby, the tag's position in the global environment can be obtained in terms of coordinates. The accuracy of relative position between tag and robot depends on the abilities of the RFID system. In most cases it is relatively inaccurate and is strongly influenced by the reading range and the ability to detect an approaching or moving away from a tag.

However, in order to fulfill a navigation task the robot needs to know at least information of how (e.g. in which direction) to find the next landmark. More generally spoken, the mobile robot requires knowledge about the current position and orientation relative to the path towards an envisioned goal.

Therefore, the combination of the RFID system with other sensor systems on the mobile robot is needed. Ultrasonic or laser based range measuring system are especially suited for this. They are able to provide a relatively accurate image of the shape of the surrounding, local environment. Moreover, the scanning of the environment does not depend on infrastructural preparations. However, using the obtained range information for map matching techniques has a number of serious disadvantages as described above and is not reliable enough for most applications of mobile robots. Moreover, for obvious reasons we do not want to store a geometric map of the entire environment in the robot. Instead, as the RFID tag provides global knowledge about its position and the other sensor systems provide locally accurate information about the shape of the current surroundings we suggest the use of a topology-based global landmark navigation supported by local geometric navigation robustly combining the advantages of both systems.

User defined Data In the tag's own RAM we store data which is used by our navigation system. In order to provide a functionality as described below we propose to store the following data:

- *The tag's global position* (x, y, z) is needed to estimate the robot's current position that is necessary to reach any reachable goal in the robot's environment.
- *Environment Class.* This is a classification of the near surroundings of the tag. These classes are needed to make global navigation decisions possible. They can be easily recognized due to easy detectable features of the near environment.
- *Environments position*, i.e. the global position of the classified environment. This data is used to compute the robot's exact global position, when needed. This can be done easily after re-classification of the environment (see below).
- *Further optional data*, e.g. references to hierarchically arranged subareas. Future research might investigate the feasibility to store information of the complete environment in each tag.

In this paper we investigate the use of some kind of internal map in the robot's memory, but these approaches are applicable to more distributed and decentralized architectures, as well.

Classification Each location marked by a tag has to be classified corresponding to its geometry, so that the robot is able to fulfill a local navigation action in order to accomplish a global-navigation task. These local actions can be subdivided in two phases, the *objective* and the *orientation phase.*

- In the objective phase, the navigation system sends steering commands to the control architecture of the robot. This objectives let the robot follow the left/right wall, turn a specific angle and go straight, or let minimize the distance to a given position. The necessary data to generate these commands are computed by the re-classification process described below.
- In the orientation phase the robot combines its knowledge about *origin*, *target* and *environment class* to determine the new direction that leads to its goal.
  This could be easily explained by the following example. Suppose the robot has to travel from tag t_1 to t_4 via the crossing marked with tag t_3. Then the robot has to know, that the class of the environment of tag t_3 is *crossing*, the reachable tags of tag t_3 are (t_1, t_4, t_5, t_2) ordered counter-clockwise from the centerpoint of the crossing.

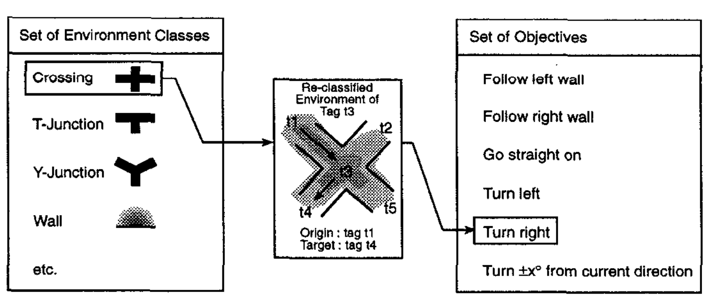

Figure 3: Generating an objective using the information stored in the tag t_3 about the current environment class.

The robot can combine this information to generate the objective '`turn right`'.

VII. Re-Classification

Due to the relatively large detection range of RFID systems the resulting position estimation based only on RFID is too inaccurate for direct position-based navigation. However due to the unique identification RFID tags are ideal for the use as landmarks. First, the use of RFID tags prevent the error of dead reckoning to grow without bounds and therefore indirectly supports the map-matching process. Furthermore, in contrast to the above mentioned map-matching techniques RFID systems would inherently solve the problem of unique matching of a stored, global map and the local map. The technique used to solve this problem is called re-classification, i.e. the process of searching for an expected environment class in the robots view of its current local environment.

A. The local occupancy grid map

Simulation and experiments showed that noisy sensor signals make it difficult to extract features of the local environment with a low error probability only from the latest sensor input. Therefore a local grid map is used to re-classify the robot's local environment. A grid map is a technique to accumulate sensor input over time to get more detailed and reliable information about the robot's environment.

This grid map covers a square of the surroundings of the robot up to its maximum sensor range and is subdivided in $m \times m$ cells. Our experiments using an ultrasonic-sensor with a reading range of 5 meters showed a grid of 64 × 64 cells to deliver sufficient accuracy. Each grid-point is mapped to an integer which is related to the probability of the surrounding cell being *occupied*. A cell is occupied if it is impassable for the robot. It is called *free*, if the probability of being occupied is significantly low. Each time a range-scan of the environment determines that a cell is free, its probability of being occupied is decreased. As the local grid moves with the robot the local map will cover "unexplored space" as well as parts of explored environment will move out of maps range. In these cases the unexplored space will be pre-set "occupied" and information shifted out of the local map will be disposed.

B. Feature extraction

The features extracted from the grid map is a polygon which covers the free space in the current map. A vertex of the polygon is computed as follows. The point of intersection of a ray outgoing from the centerpoint of the grid map with the first occupied grid-cell is a vertex of the polygon. Iteration of this method for several directions leads to a starlike polygon. This polygon can be matched with the environment class implied by the detection of a tag. If this match cannot be established the probability of being free has to be adapted.

C. Relative navigation

Furthermore, the robot's position relative to its near surroundings can be computed from the local map. The error then only depends on the accuracy of the robot's sensors and the short time dead reckoning error during construction of the local map. As the local map forgets knowledge about environment that shifts out of the map's range, the average error imposed on the estimated position by dead reckoning is related to the size of the local map. If this relative position and the feature-polygon is known, the commands used in the objective phase can be computed easily.

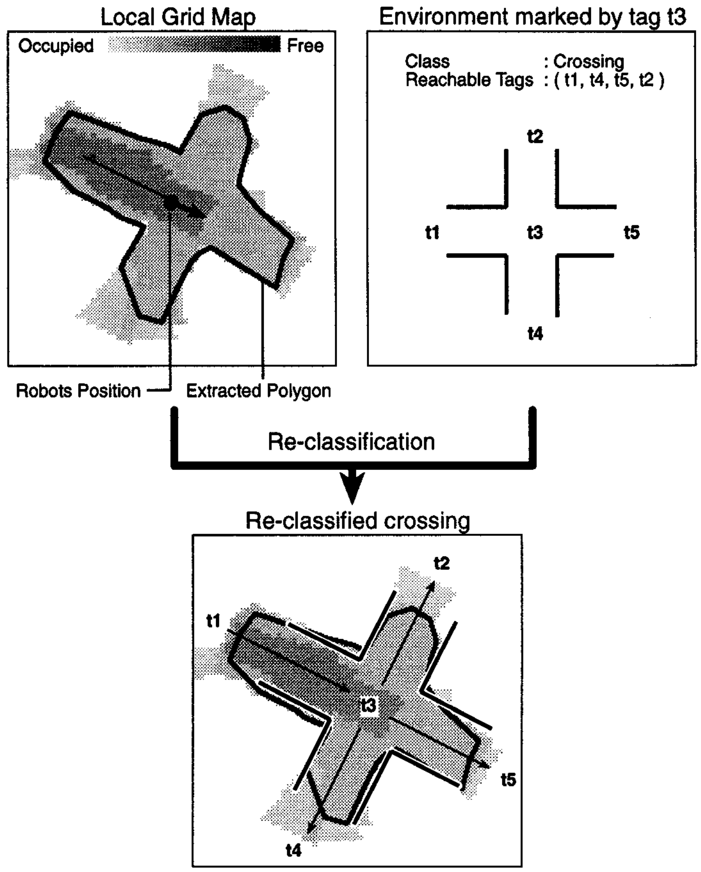

Figure 4: Re-classification of a crossing through a local grid map and class information from tag *t3*

VIII. Path planning

The used control architecture of the presented mobile robot is able to navigate through its local environment based on compositions of behaviors. Furthermore, the system is able to make navigation decisions wherever a tag is placed in the environment. By the combination of these abilities the robot can navigate along an arbitrary sequence of known tags, called a *path*. In order to be able to compute paths on-board a topological global map has to be stored in the robots memory. This map is implemented as a edge-weighted d-graph where the vertices of the graph represent RFID tags. An edge (a, b) pointing from node a to node b represents the possibility to navigate from the position marked with tag a to the position market with tag b. The edges are weighted with the *costs* of traveling along this edge and a sequence of objectives that enables the behavior-based control architecture to make the robot travel from an edge's starting node to its target node. Referring to the costs provided in the graph it is easy to compute the "cheapest" paths in this d-graph for example using the Floyd-Warshall-Algorithm. Hereby, the robot is now able to reach an arbitrary goal-tag by sequentially driving to all tags in the computed path, starting at the current location.

IX. Reaching unmarked positions

In general a robot's goal might be any given position in its environment and therefore might not be marked with a tag.

To reach a goal that is given by a (x, y, z)-coordinate instead of a tag the robot first determines a target tag, i.e. the RFID tag which coordinates are the closest to the given goal. Then it starts homing towards this tag using the navigation technique shown above. After the target tag is reached, the robot has to use a different navigation technique, which allows it to reach any given point with the accuracy provided by the odometry. In [10] Kamon and Rivlin presented the algorithm DistBug based on an approach presented by Lumelsky and Stepanov [11] that has been proven to reach any goal in an unknown environment, if it is reachable. As the robot is able to compute its global position as soon as the target tag is reached, it can use an adaptation of this algorithm to proceed. The DistBug-algorithm consists of two modes. In mode

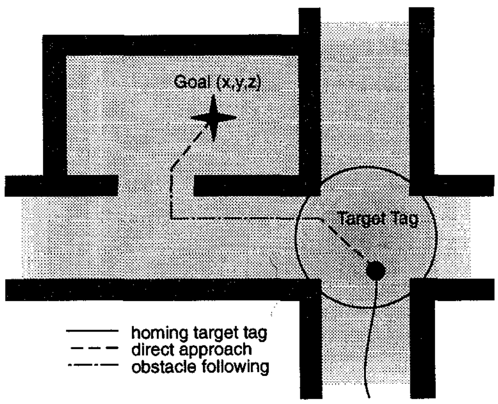

Figure 5: Reaching of an unmarked goal at position (x, y, z) from a known tag position only with local environment information

one the robot moves directly towards the goal. In mode two it follows an obstacles boundary. The following shows the principles of DistBug as presented in [10].

1. Go directly to the goal, until one of the following occurs:
   (a) The goal is reached. Stop.
   (b) An obstacle is reached. Go to step 2.
2. Choose the boundary following direction. Follow the obstacle boundary until one of the following occurs:
   (a) The goal is reached. Stop.
   (b) The free range in the direction to the target guarantees that the next hit point with an obstacle will be closer to the target than the last hit point. Go to step 1.
   (c) The robot completed a loop around the obstacle. The target is unreachable. Stop.

Because the computation of positions during the DistBug-algorithm is based on odometric measurings, the distances between the goal and its closest tag must not be too large. Therefore it is important that the places to be marked with a tag are chosen carefully.

X. Conclusions

In this paper a navigation technique based on radio frequency identification has been presented for mobile robots [2]. RFID tags were used as landmarks enabling the robot to robustly fulfill a global navigation task due to the secure and unique identification of the tags. The technique of re-classification solves the problem of matching a current, local map of the robot's surroundings to a class describing the current environment and provided through the identification of the tag. In contrast to recent map matching techniques this approach uses unique RF identification instead of map building based on inaccurate odometry or similar methods. Global navigation based on topologic maps is inherently supported by the behavior based control architecture. The encouraging results using radio frequency identification promise robust and cheap mobile robot navigation while requiring very low infrastructure preparations even in dynamic changing environments.

[2] Notice that the entire control system for the mobile robot runs on a single PC. The algorithms are designed to not require high computation power like several workstations.

References

[1] Liqiang Feng, Johann Borenstein, and H.R. Everett, "Where am i? sensors and methods for autonomous mobile robot positioning", Tech. Rep. UM-MEAM-94-21, University of Michigan, 1994.

[2] Ulrich Strunz, *Umgebungsmodellierung und sensorunterstützte Navigation für mobile Roboter*, PhD thesis, RWTH Aachen, 1993.

[3] P. Hoppen, T. Knieriemen, and E. Puttkamer, "Laser-radar based mapping and navigation for an autonomous mobile robot", in *Proceedings of IEEE International Conference on Robotics and Automation*, May 13–18 1990, pp. 948–953, Cincinnati, OH.

[4] James Crowley, "World modeling and position estimation for a mobile robot using ultrasonic ranging", in *Proceedings of IEEE International Conference on Robotics and Automation*, May 14–19 1989, pp. 674–680, Scottsdale, AZ.

[5] A. Kak, K. Andress, Lopez-Abadia, and M. Caroll, "Hierarchical evidence accumulation in the pseiki system and experiments in model-driven mobile robot navigation", *Uncertainty in Artificial Intelligence*, vol. 5, pp. 353–369, 1990, Elsevier Science Publishers B. V., North Holland.

[6] Matthias Oliver Berger, O. Kubitz, and Th. Sperlbaum-Weigt, "Towards a formalization of autonomous agent architectures", in *SIRS '96*, José Santos-Victor and James L. Crowley, Eds., July 22–26 1996, pp. 25–32, Lisbon, Portugal.

[7] R.A. Brooks, "A robust layered control system for a mobile robot", *IEEE Transactions on Robotics and Automation*, vol. 2, no. 1, pp. 14–23, 1986.

[8] R.A. Brooks, "Intelligence without representation", *Artificial Intelligence*, vol. 47, pp. 139–160, 1991.

[9] L. Steels, "Building agents out of autonomous behavior systems", in *The Artificial Life Route to Artifcial Intelligence. Building Situated Embodied Agents*, L. Steels and R. Brooks, Eds. 1995, Lawrence Erlbaum.

[10] Ishay Kamon and Ehud Rivlin, "Sensory based motion planning with global proofs", in *SIRS '95*, Carlo Colombo and James L. Crowley, Eds., July 10–14 1994, pp. 249–256, Pisa.

[11] Vladimir Lumelsky and Tim Skewis, "Incorporating range sensing in the robot navigation function", *IEEE Transactions on System, Man, and Cybernetics*, vol. 20, no. 5, pp. 1058–1069, September 1990.