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by

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A Tree-Climbing Robot for Invasive Insect Detection

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Abstract— **This paper reviews progress in the development of a scansorial robot for invasive insect detection. It discusses the motivation for our approach, provides design considerations and implementation details, and presents progress to date. One notable feature of the robot is its use of vSLAM to map the tree under study. The robot is currently under development at WPI and this paper provides a summary of its status and future plans.**

Keywords- 3D Reconstruction, ScansorialRobot, Visual SLAM, automated inspection, tree inspection.

I. INTRODUCTION

Asian Longhorn Beetle (ALB) is an invasive insect species that poses a serious threat to the North American hardwood industry. In order to eradicate ALB, extensive surveys must be conducted around known infestation areas, infested trees destroyed, and neighboring uninfested host trees treated with pesticide. The beetle is difficult to observe directly, rather, it is generally detected indirectly through surveys that look for frass, oviposition wounds, and insect exit holes on tree branches and trunks (Figure 1). The United States Department of Agriculture (USDA) is the lead agency for the ALB eradication program. Currently, the USDA conducts surveys of trees using human climbers: a slow, error-prone, hazardous, and expensive process. A medium-size maple tree can take an hour to survey by a team; with almost 2 million trees surveyed to date around the Worcester, MA infestation area this becomes an expensive proposition. Estimated damage of $3.5 billion annually [11] is caused by wood-boring insects such as ALB. We are developing a tree climbing robot to efficiently conduct surveys and to support other scansorial activities, such as environmental monitoring. The robot is equipped with a single camera to generate a 3D visual representation of the tree surface that can be used for detailed examination to detect infestation. The next section gives an overview of previous reports about scansorial robots. This is followed by the description of the signs used for the detection of the ALB, and our approach and the various design decisions to attack the task. Section V describes the mechanical, electronics and software design, and Section VI discusses the Processing steps. Finally our results and future work are discussed in the last section.

II. RELATED WORK

Rise [1] and Dynoclimber [2] have demonstrated robots capable of climbing trees. These scansorial robots could be used in search and rescue, surveying, and monitoring applications. Much work has been carried out on the electromechanical design of the robots and controllers, but there has been less development of computer vision algorithms on scansorial robots for surveying and mapping. By having the robot circumnavigate a target tree, the different views give information about the tree surface at various angles. [3] describes a technique for 3D reconstruction of archeological artifacts, which shares some problem characteristics with mapping trees. Photogrammetry has developed solutions to 3D reconstruction based on Structure-From-Motion, but these techniques use offline processing and require extensive camera setup and calibration, hence are not immediately applicable to our application. [4] describes a reconstruction technique that relies on a stationary camera with different views of the object for reconstruction. This is similar to our problem, except that they use a stationary camera to map a moving object whereas we use a moving camera to map a stationary object. This problem is amenable to attack using Visual Simultaneous Localization and Mapping (vSLAM), a map building technique which uses visual odometry and photogrammetry to generate and refine world models as sensed by a mobile robot. [6-8] describe the vSLAM algorithm and various improvements. [9] compares the two most common approaches in vSLAM.

Figure 1. Adult Asian Longhorn Beetle and characteristic 3/8 inch exit hole. Photograph courtesy Dr. Clint McFarland, USDA.

III. DETECTING ASIAN LONG HORN BEETLE

Most of the ALB’s life cycle is spent inside tree trunks as larvae, which makes it difficult to detect during the initial stages of infestation. There are five signs to detect the Asian Longhorn beetle.

A. *Oviposition holes*

These are scars left on the bark by the female beetle when she chews tree bark in preparation for laying an egg. She then lays a single egg in the resulting hole, repeating approximately 35 times. The scar is visible even many years after the egg is laid, but is difficult to distinguish from natural scars. The oviposition holes are generally located in the upper branches of the tree. The egg hatches and the larva enter the hardwood. Once in the hardwood, the larva is difficult to detect. Research on acoustic methods to detect ALB larvae is underway [12], but these methods are not suitable in noisy urban environments.

B. *Exit Holes*

After the larva pupates – from one to two years after the eggs are laid depending on climate – the adult beetle emerges and chews out of the tree, creating an exit hole. Exit holes are 3/8 inch uniform size circular holes which are easy to detect, remaining visible indefinitely. However, by the time exit holes are visible, the beetles have emerged and have potentially spread to other trees.

C. *Frass*

The frass and boring dust produced by the feeding larvae are expelled out through the oviposition hole. Frass is also left behind when the exit holes are created. Old frass may be difficult to detect, as it can be washed away by rain or blown away by wind. It is sufficient to detetct the presence of oviposition or exit holes as the frass is a byproduct of it.

D. *Beetle*

ALB range from 0.75-1.25 inches long, with very long black and white antenna. The adult beetle is shiny and coal-black with white spots. They are visible brfiefly during the summer when the beetles feed on the leaves and mate.

E. *Leaves*

The ALB has a specific feeding pattern. They chew the veins of the leaves leaving the reminder of the leaves intact. The feeding marks left on the leaves can be used to detetct the presence of the ALB.

Locating infested trees is based entirely on visual surveys. Initially, surveys were done from the ground using binoculars; however, ground-based surveys fail to detect many cases of infestation because the initial infestation often occurs in the crowns of trees. Ground-based surveys are currently supplemented using bucket trucks and tree climbers, revealing many more infested trees.

IV. APPROACH

To explore research issues involved in scansorial robots, we have developed a prototype tree climbing robot as shown in Figure 2. The robot can be equipped with either 4 or 6 legs, with 3 servos on each leg: two at the shoulder and one at the elbow, providing adequate degrees of freedom for walking and climbing. The design is modular, enabling removable of the middle legs if required. The robot has a wireless camera mounted on the front pointed downward at an angle of approximately 45 degrees which gives a view for navigation as well as imaging the tree surface. The robot was designed to carry a single camera, rather than a stereo pair, in order to minimize weight and conserve power. Images captured by the robot are sent to a workstation on the ground where image processing, map generation, and display operations will be carried out. The workstation also serves as the operator's console (Figure 3). The robot is designed primarily to travel up and down; however, it can also turn to circumnavigate the tree and acquire images from multiple viewpoints. To provide detailed information for surveying, dense tree surface information needs to be generated. The image processing algorithms must be robust to handle a wide range of lighting conditions, ranging from direct sunlight to deep shade. The representation of the tree in 3D must also be robust and should easily handle changes in the tree environment. At the same time, the tree representation must be flexible to incorporate observations from multiple viewpoints. vSLAM is a family of computer vision algorithms used for mapping and generating 3D information from image and distance/depth data. It has been applied to generating a dense map of world objects [10]. vSLAM was initially developed for mapping building interiors, including rooms and hallways. In these applications, the robot is looking outward, through freespace. In our application, the robot is looking inward, toward the tree, essentially requiring an "inside-out" approach to vSLAM. Thus, we have tailored the vSLAM algorithm for its application in scansorial robotics for mapping the tree surface.

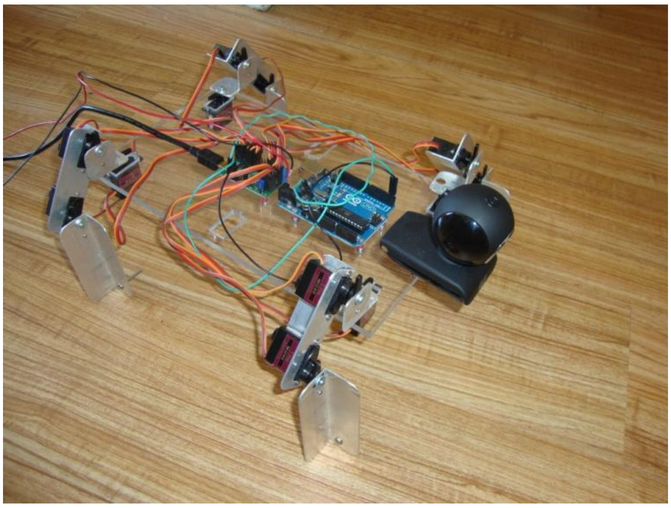

Figure 2. Tree climbing robot chassis with 4 legs and clear acrylic body. Two extra legs can be fit in the middle at the provided slot. Battery not shown.

There are additional challenges to implementing vSLAM on tree surfaces. One is the need for a dense depth map. As we detect many feature points for matching, performing accurate correspondences becomes more difficult. A tree's curvature also provides an interesting challenge as it provides views of the same point from different angles and the common assumption of planar surfaces does not hold.

We see that Visual SLAM is a suitable algorithm for mapping a tree surface with a moving camera. It has also been shown to have good performance in an outdoor environment; hence it can be considered as an appropriate solution to mapping trees [7]. Because vSLAM is a real-time algorithm, it is more appropriate for surveying applications than Structure-From-Motion algorithms that require off-line processing.

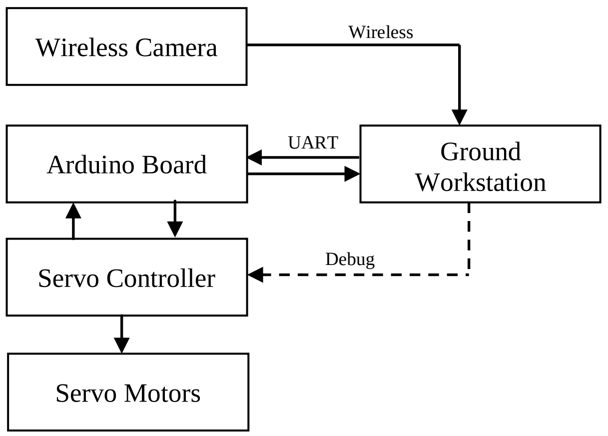

Figure 3. Overall architecture of the system.

V. DESIGN

A. Mechanical

The robot consists of a modular design with 4 to 6 legs. The legs can be removed according to the need. The total weight of the robot with 4 legs is around 685g. Each leg features a spike, consisting of a sharp screw end, to firmly grip the outer bark of the tree (Figure 4), similar to how insects or clawed creatures climb trees. Each leg is a 3-DOF kinematic chain with three actuators.

We are currently comparing the tradeoff between 4-legged and 6-legged designs. The biggest differences are gait, weight, stride and power. Six legs provide more varied gait options as only 3 points of contact on the tree are needed for stability. The 4-legged design only allows simple gaits in which only one leg moves at a time. The 4-legged design allows each leg to take a longer stride as the middle legs will not obstruct movement of the front and rear legs. The legs are the heaviest part of the robot; thus, by reducing the number of legs the weight is reduced. Most of the power is used to drive the legs. Each leg is actuated by 3 servos; thus, by reducing the number of legs the power required is also reduced.

B. Electronics

The robot was developed with the ultimate aim of being used for commercial purposes. Therefore, most of the electronic equipment is designed using off-the-shelf components. The robot has an onboard AVR microcontroller (Arduino Uno Board) and a servo controller (Polulu Mini Maestro Servo controller) for gait control and communication. There is currently no feedback from the servo motors for closed loop control. The Arduino Uno Board was selected due to its availability, low cost, and technical support. Metal gear micro servos were selected because of their high torque to weight ratio which ensured low weight. To reduce weight further, the robot is powered by an external power supply link rather than an onboard battery.

Figure 4. The robot gripping a tree log using the spike type legs.

C. User Interface

The robot's User Interface (UI) is designed using Qt4, which has good integration with the OpenCV package on which the image processing steps are implemented. It was designed keeping in mind the need to accommodate users inexperienced with robot control. The user interface consists of simple buttons that allow the operator to navigate up, down, left or right (Figure 5). The controls are also mapped to the keyboard for further flexibility and ease of use. The UI also displays useful information, including the status of the robot. The UI also has auto-move commands that enable the operator to issue continuous actuation of the robot. The detailed image processing and analysis steps are discussed in the next section.

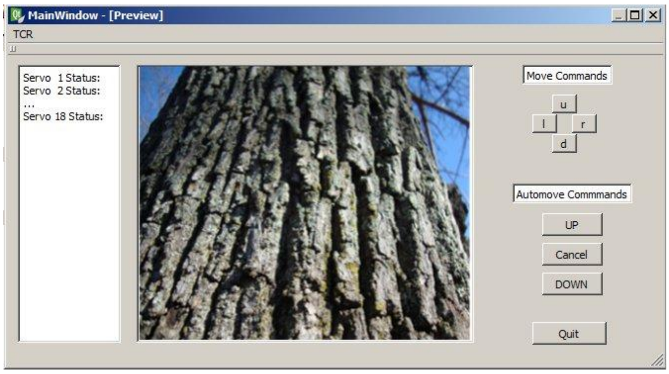

Figure 5. Prototype user interface, including simulated image of tree as seen by robot.

VI. PROCESSING STEPS

We present an outline of the steps that we follow for implementing Visual SLAM to generate 3D tree models (Figure 6). A filter-based approach is selected to implement the vSLAM algorithm. In this approach, the state of the system consisting of the robot pose and location along with the observed map features is estimated and updated iteratively as new observations are made.

A. *Image acquisition*

The images from the monocular camera onboard the robot are transmitted to the workstation computer over a wireless connection. The images are stored on the workstation where the processing is carried out.

B. *Preprocessing*

The images from the camera are preprocessed by removing background details irrelevant to the tree by image masking. The remaining tree image is converted to a luminosity-invariant Lab color coordinate system to remove the effect of lighting variations that occur in outdoor environments.

C. *Feature Detection*

A reliable and fast feature detection algorithm, SURF [9] is used to determine the location of feature points (M_k). SURF uses a robust feature detector and compact feature descriptor which makes it suitable for real time operation. The detected feature points are added to a feature database upon which the model is built.

D. *Location and Pose Estimation*

An estimate of the camera location is made based on the system model and the estimates of the features in the map. The noise in the estimates will decrease as pose estimates converge with more observations. The current state of the camera X_k is obtained in this step. With the camera state approximately known, the distance estimates Z_k to the features M_k are also calculated and added to the database. Also details from the current estimate of the map/model are used to further refine the location and pose estimate.

E. *Registration and Matching*

The next step consists of vSLAM / 3D registration where the collected feature points M_k and distance estimates Z_k from consecutive image sequences in the camera coordinate frame are mapped to points in the 3D world coordinate space of the tree. An Extended Kalman filter is used to update the estimates of the positions of the features in the world coordinate space and the camera state X_k. The state model consists of the robot's position (x, y, z) and pose (yaw, pitch, roll) along with the position of the features. In the current model the feature points are assumed to be static.

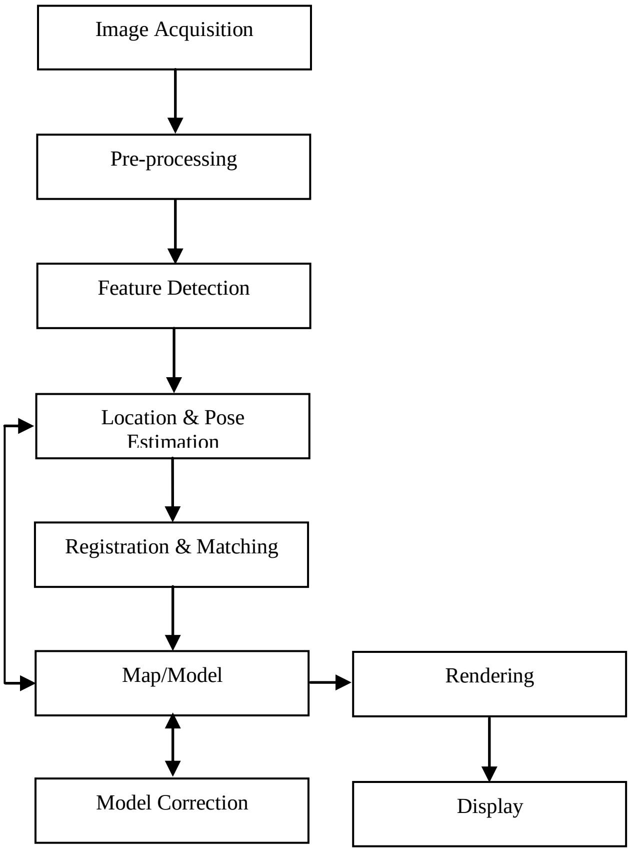

Figure 6. Flow chart describing the steps from the image acquistion to the tree model generation.

F. Map/Model

The map consists of all the feature points observed so far registered to the global coordinate frame of the tree. The map is also used in the odometry estimation.

G. *Rendering*

The representation of the model in a form suitable for visualization by human observers is done at this step. Based on user-specified viewpoints, different views of the tree are generated. The views need to give conclusive information to confirm or disconfirm the presence of 3/8 inch exit holes. In order to produce dense information, a triangulation can be generated using the feature points as mesh points.

H. *Model Correction*

The model is updated and corrected as new images are acquired. Loop closure occurs when the camera observes the same feature point again from a different viewpoint. Model correction is performed at longer intervals compared to model updating to reduce the computation time. The model correction further improves the accuracy of the tree model generated.

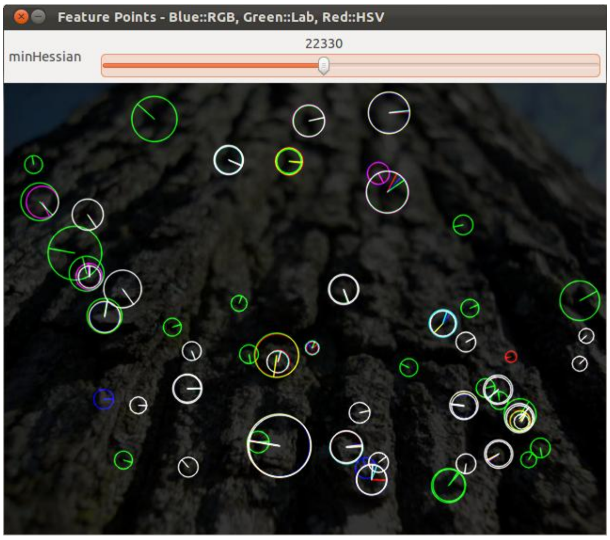

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Figure 7. SURF algorithm run on a tree image. Results using the same algorithm on different color spaces are shown in Blue: RGB, Green: Lab, Red: HSV. Color combinations show features detected in more than one color space as Aqua: RGB and Lab, Purple: RGB and HSV, Yellow: Lab and HSV. White features indicates where all 3 color spaces find the same feature. Lab color space finds features (Green) that other color spaces miss.

VII. RESULTS

A novel robot has been designed for climbing trees and performing visual inspection. It is currently being built and tested. Additional work is in progress to further develop the robot. We have collected a data set containing tree images from various viewpoints simulating the imagery that will be acquired by the tree climbing robot. The SURF algorithm has been implemented for feature detection. We compared the performance of the SURF feature detector using Luminance-Alpha-Beta (Lab), HSV, and RGB color spaces in order to evaluate their performance under different lighting conditions, and found that Lab detects more features than the other color spaces (Figure 7). The Extended Kalman Filter based vSLAM is under implementation.

VIII. FUTURE WORK

A. Mechanical

The mechanical design of the leg needs to be studied in detail to gain a better understanding of scansorial robots. Other mechanisms for gripping the tree such as micro claws need to be studied. The varied nature of tree surfaces with varying friction coefficients and structure poses an interesting challenge.

B. Electronics

The robot is planned to be tele-operated with fixed gaits. Automatic gait evolution is another aspect of the robot which requires further work. Better control and communication algorithms on the microcontrollers are expected in future designs.

C. Software

Path planning and navigation in scansorial environment is another aspect that needs further investigation. Autonomous exit-hole detection needs to be incorporated in the processing step. The vSLAM algorithm needs to incorporate moving elements such as insects to further improve the robustness. Also the vSLAM algorithm can be further adopted to incorporate the time changes that occur in the trees over a long period, thus providing more details to survey teams.

The completed robot is expected to be a valuable tool for the USDA to survey trees reliably, efficiently, and at low cost.

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