3D Tracking of Building Processes in *Macrotermes*

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Abstract

Mound-building termites of the genus Macrotermes *actively reshape their physical environment in ways that benefit their colony. Previous studies of* Macrotermes *have focused on the response of termites to stimuli such as water and pheromones. Observations typically quantify relative preferences between stimuli or the bulk movement of building material. However, for fuller insight into the construction process, we seek a greater understanding of how individual termites react to partially built structures including their detailed geometric form. Here we present tools we have developed to produce detailed height maps of soil terrain in experimental petri dishes, including ongoing work toward continuous scanning for dynamic height maps while termites actively rearrange soil. These tools inform our ongoing study of how termites build complex large-scale structures through local interactions with their environment.*

1. Introduction

The two African termite species *Macrotermes michaelseni* and *M. natalensis* are among nature's greatest architects, building complex mounds several orders of magnitude larger than themselves [1]. Although individual termites are vulnerable to predation and the harsh environment of their desert habitat, their large (up to two million individuals) colonies are not. Together, individual termites, their mound, and their nest structures form a so-called extended phenotype [2]. The mound, often reaching several meters in height, is not actually inhabited by termites; however, it both protects and regulates gas exchange in the nest beneath it. Acting as a sort of artificial lung, the mound filters high-frequency turbulent winds through a series of small tunnels along the exterior of the mound, leaving a low-frequency "breathing" in the central chimney, promoting atmospheric regulation in the nest [3]. Although this functionality is known, the process of mound construction is poorly understood.

Engineers have drawn inspiration from these natural systems to inspire modern architecture as it moves toward more energy-friendly ventilated buildings [4], and also in seeking ways to achieve such massively parallel and robust coordination between independent agents [5,6]. Following this line of thought, we are interested in how termites seem to solve the problem of decentralized coordination so effectively. How do the separate local choices of individuals during the building process result in a functional global structure? To answer this question we need detailed information about the local decisions termites make.

In this paper we present methods for gathering detailed geometric data about construction dynamics in controlled petri dish environments. With these methods, we hope to better understand how local termite-termite and termite-environment interactions lead to large-scale functional structures. Specifically, we hope to collect quantitative high-resolution data on how termites rearrange soil over time, and what geometric or chemical properties constitute features of interest. We describe equipment for two systems designed to gather such data, along with preliminary results. The first system uses structured light scanning [7] to record three-dimensional height maps of soil in a

dish before and after it has been manipulated by termites. The second is an ongoing effort to produce a dynamic height map continuously updated while termites are active in the dish, using a laser scanner. Both systems allow us to—to an increasing degree—capture detailed geometric data on termite building behavior in controlled experimental settings.

2. Related Work

African *M. natalensis* species were first described in 1898 by Haviland and *M. michaelseni* in 1914 by Sjöstedt [1]. However, despite the impressive activities demonstrated by these insects, they remain poorly studied compared to other social insects such as bees and ants. This lack of detailed behavioral knowledge is at least partially due to the difficulty of working with them. Observations in their natural underground dwelling are impractical, and their behavior seems to rapidly deteriorate with the time they spend removed from their colonies.

Current in vitro methods observe captured termites in petri dishes or other enclosures as experimental arenas. Observations focus on broad measures of soil movement or manual observation of termite actions and interactions [3]. Automated video tracking is complicated by the fact that termites are sensitive to surface conditions and moisture, so experiments are typically carried out on damp soil, which provides poor contrast. Efforts to improve contrast include marking termites with paint or allowing them to drink fluorescently dyed water, which shows up bright yellow in their abdomens [3]. However, bits of soil manipulated by the termites remain difficult to distinguish from one another and from the background soil field, interfering with automated tracking using visual input only.

In vivo experiments include destructive measurements cutting mounds into slices, analogous to sectioning tissue, to gain insight into the 3D structure of the internal tunnel network [1,3]. Another approach has been to insert polystyrene beads of different colors into the nest, which termites transport along with soil. Observing the mound surface and eroded soil around the mound allows tracking the bulk movement of soil [3]. Very recent and preliminary efforts use "termite towers", in which two parallel glass plates are inserted into and projecting from the mound along a surface conduit. As termites respond to the disturbance and rush to repair the hole, their building progress can be observed through the glass plane. However, this method too provides only broad information about building progress and intensity, not detailed geometry

of intermediate structures or actions of individual termites.

3. Structured Light Scanner

In our efforts to obtain detailed information about termite construction activity, we investigated several different 3D measurement techniques: stereo vision, structured light scanning, and laser-line scanning.

Though stereo-triangulation is a common task in machine vision and software for dense stereo-matching is commercially available, the packages we tried did not provide satisfying results; in particular they had many outliers, probably due to low contrast in the soil. Structured light scanning using DAVID® Laserscanner software (http://www.david-laserscanner.com/), however, provided an effective and inexpensive solution (Figure 1).

The setup was as follows. A petri dish was prepared with soil covering the bottom 4mm, sometimes with different experimental conditions in different regions, e.g., one half having wetter or pheromone-laced soil. The petri dish was then scanned using one camera (Canon T2i) and a small projector (iGo UP-2020) projecting a series of patterns on the target, Figure 1-A. Each scan took about 30 sec, and was repeated three times from three angles 120º apart to avoid occlusions. The three scans produced point clouds, which were automatically aligned in software using markers on the petri dish.

This setup achieved sub-pellet (better than 0.5mm) resolution. After an initial scan, we added termites and let them behave for a fixed period (typically 30min), recording their actions with an overhead video camera. Afterward, the dishes were put into a freezer to immobilize the termites. They were then carefully removed, and the final structure was scanned again. The final soil configuration would typically be within a total height difference of 8mm compared to the initial surface. This process allowed us to obtain geometric data like that seen in Figure 1-B. Next, the aligned point clouds were processed into a height map in Matlab (Figure 1-C). The video data recorded were used for complementary tracking of individual termites using Ctrax [8], Figure 1-D.

While the focus of this short paper is on tools rather than on the preliminary results so far obtained, replicates of these experiments have provided statistical evidence supporting and quantifying previous results about termite preferences for wetter soil and a putative cement pheromone [3], and exploring their reactions to geometric features in an otherwise homogenous environment.
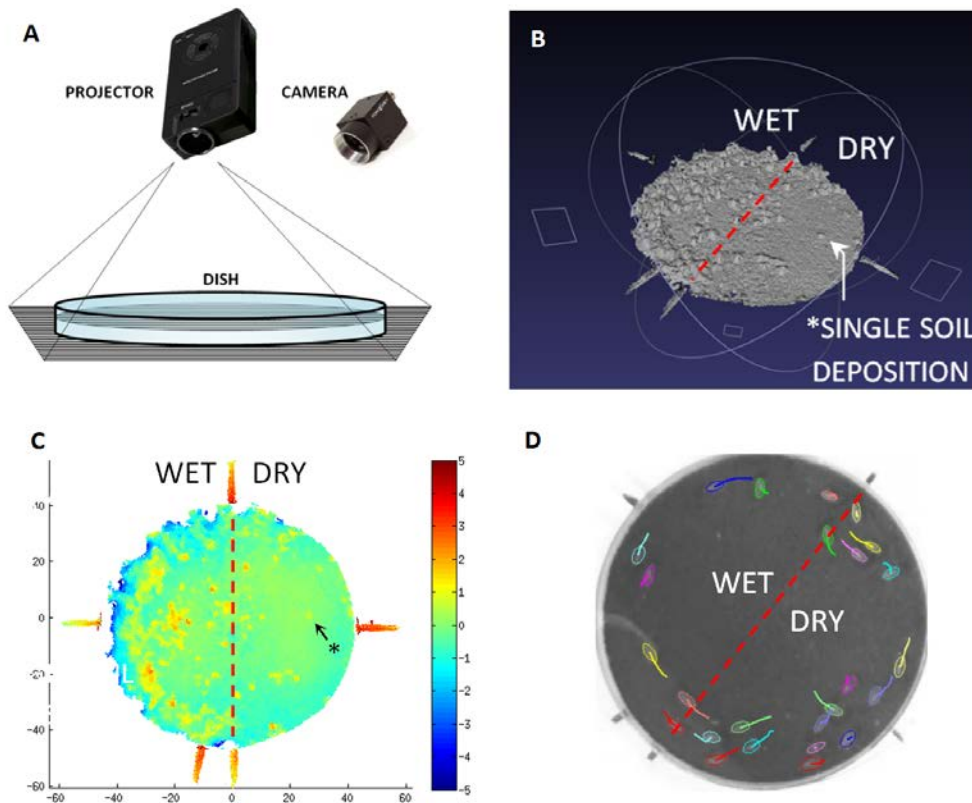
Figure 1 Structured light scanner. *A*: Experimental setup. *B*: 3D scan of a dish, using DAVID-Laserscanner software, after 30 min of activity with 25 termites. Initial state of soil in the petri dish was level, one half with twice the water content of the other, separated by a thin plastic divider below the surface (dashed line). Objects outside the dish are toothpicks used as features for alignment of multiple camera views. *C*: Matlab height plot. White along the dish edge indicates that termite digging reached below the level occluded by the sides of the dish. This depth approximately coincides with the bottom of the dish. A preponderance of building activity on the wetter side is evident. *D*: Snapshot of the overhead video output using Ctrax software to track termite motion.

While these initial and final scans give detailed 3D geometric information about cumulative termite building activity for a fixed period, they do not provide such information for construction dynamics within that period. This consideration motivates the experimental apparatus described in the next section.

4. Laser Scanner

We built a multi-camera and line-laser setup as shown in Figure 2 (top). In contrast to the structured-light approach, which depends on a scene remaining static (i.e., without termites) during a time series of projected patterns, this setup gives instantaneous height information for a line of points illuminated by the laser. The laser is mounted to provide a vertical plane of illumination, passing through the center of the dish and rotating by a small angle between snapshots, giving a time series of updates like a radar sweep.

Three cameras (Point Grey®, FMVU-03MTM-CS) placed 120º apart take a set of three images, allowing 3D triangulation of illuminated points, for each position of the line laser. The laser (AixiZ, AIX-650-5-1230) can rotate in steps as small as 0.2º, corresponding to <0.2mm resolution at the edge of an 87mm-diameter dish. A full 360º scan takes under 3min. A fourth camera mounted directly above the dish records video data for tracking. The laser is pulsed such that frames taken by the first three cameras with the laser on are interleaved with frames taken by the fourth with the laser off and strong ambient lights on. The video can be used for complementary tracking information as well as to identify the locations of termites, to disambiguate termites from soil in the height map. Because termites of the species of interest are blind, we believe their behavior should be unaffected by the laser illumination. Figure 2 (bottom) shows a time-exposure photo of a scan being taken
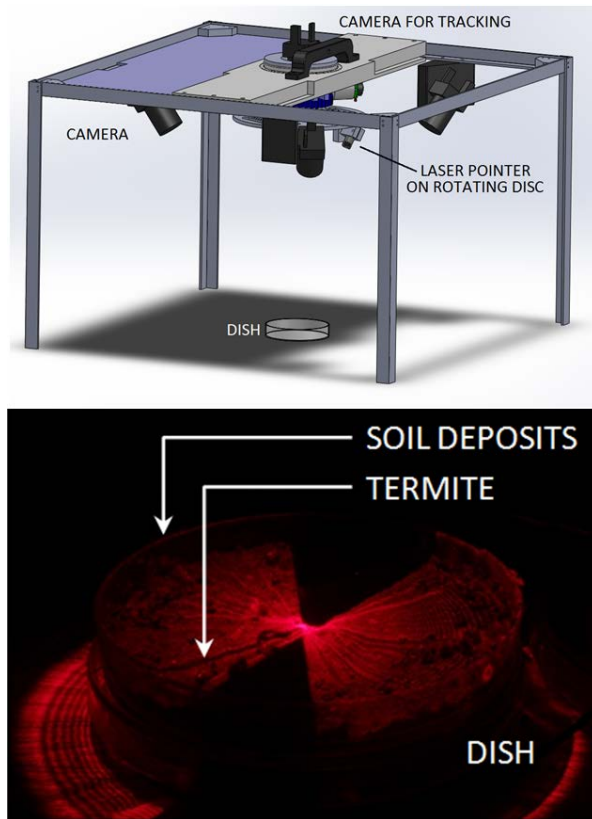
Figure 2 Laser Scanner. Top: Recording rig, showing 3 cameras, the line-laser, and an overhead camera for tracking. Bottom: Long exposure photo of a dish with termites, during a continuous scan.

while termites are active. Analyzing this data is an ongoing effort.

Our hardware allows for rotating multiple non-intersecting line-lasers, which would allow us to compute height data along each laser line for every captured frame, thereby greatly increasing the data acquisition rate.

5. Final Remarks

In this paper we have presented current and ongoing work towards the goal of understanding building behavior in two species of mound-building termites of the genus *Macrotermes*. Existing experimental methods do not provide sufficient spatial or temporal resolution and accuracy to allow automation of quantitative observations of local termite building behavior. We have described our ongoing efforts in building tools to observe how individual termites interact with small-scale geometric features. We currently have the ability to collect initial and final height maps of structures built, and are finalizing the development of a toolset for continuous 3D scanning of structures as they emerge.

With this toolset we hope to gather large detailed data sets of the process of termite construction, to help reveal the local dynamics of the insects' activity and thus allow us to better understand how this fascinating superorganism coordinates its construction process. As engineers, we would like to learn its principles of organization and apply these insights to engineered systems, such as large teams of cooperating construction robots.

We believe that sufficient data, which the apparatus presented here will allow us to gather, will help tremendously in understanding the response of these termites to the various stimuli that influence their behavior. Further, we would like to see these tools applied to the study of other insects and their interactions with their environment, e.g., nest-building ants.

6. Acknowledgements

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