EPSRC Proposal submitted via
Engineering Responsive Mode

CASE FOR SUPPORT

3D-Mapping of *Macrotermes Michaelseni* Mounds and Simulation of their Homeostatic Function: Lessons for Human Construction?

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PART 1: PREVIOUS TRACK RECORD

Personal Profile of Investigators and Collaborators

Investigators:

Dr. Rupert Soar: Dr. Soar is a Lecturer for The Wolfson School of Mechanical and Manufacturing Engineering at Loughborough University. Dr. Soar began his academic/research career at De Montfort University after his PhD studies. Dr. Soar assisted in the creation of, and then later ran, Europe's first MSc course on Rapid Product Development at De Montfort. He transferred to Loughborough University to take up the position of Lecturer in 2001. During that year, Dr. Soar was awarded an EPSRC Fast Stream grant to undertake fundamental material characterisation research for a new and novel method for the manufacture of 3D metal components using ultrasonic consolidation and, as such, is the main researcher in this field in the world. This research identified some, as yet undefined, attributes by which ultrasonic energy can be used to achieve large amounts of plastic flow which can enable fibre elements to be embedded within a metal matrix without the thermal issues normally associated with metal matrix composite manufacture.

This discovery has led to further funding which will model ultrasonically-induced plastic flow within aluminium and titanium matrix structures. The work is expected to lead to a method for the incorporation of embedded fibre Bragg grate strain measurement devices and shape memory alloy 'active' fibre, to form integral/adaptive control surfaces for high velocity wing/aerofoil structures. It is the requirement for larger and more complex, hierarchical structures which led Dr. Soar to become aware of the implications of the emerging additive manufacturing technologies when applied to the construction industry. These research interests, associated with Dr. Soar's background in horticulture and construction, prior to his academic career, has given insight into potential, multi-disciplinary, innovations in a number of areas. He will be the Principal Investigator for this project, with responsibility for its overall management and execution.

Professor Dennis Loveday: Dennis Loveday is Professor of Building Physics and Head of the Building Services Engineering Group at Loughborough University. This Group, together with the Construction Management Group, obtained a 5* rating in the 2001 Research Assessment Exercise under the return for 'Built Environment'. Professor Loveday has over 20 years experience in research applied to engineering heat transfer, energy systems for buildings and the interaction of humans with their thermal environment. He is an invited author for the Heat Transfer Section of the CIBSE Design Guide, and has published over 100 papers in these and related fields. Recent completed work relates to the measurement of convection coefficients for live human subjects, the data showing for the first time the effects of natural body movement on heat transfer. A current project involves the modelling and experimental validation of heat transfer and flow processes within double-skin facades of buildings.

Mr. HK Versteeg: Henk Versteeg is Senior Lecturer in The Wolfson School of Mechanical and Manufacturing Engineering. His main interest is interdisciplinary research with a focus on the application of computational fluid dynamics (CFD). Recently completed research projects include:- (1) EPSRC Grant GR/L69749 - "Optimisation of the application of fluid energy to hydro-entanglement process" and (2) Fully sponsored research project for AstraZeneca plc - "CFD modelling of pressurised metered dose inhalers". The latter involved the integration of experimental and theoretical methods to study multiphase flow behavior and aerosol spray formation processes for a pharmaceutical inhaler. A phenomenological spray model was integrated into the CFD codes Fluent and Star-CD to predict the development of the aerosol plume in the complex geometry of the oral cavity and upper airway. Mr Versteeg has collaborated with Prof Loveday's group on several occasions and has co-supervised a PhD research project (Harrington, 2000) in the area of CFD prediction of natural cross-flow ventilation in buildings. He is the principal author of the widely-used CFD text "An Introduction to Computational Fluid Dynamics: the Finite Volume Method" and is a consultant to industry on a variety of fluid engineering problems, ranging from pharmaceutical device design, flow measurement, heat exchanger and pump design.

Dr. W. Malalasekera: Dr. Malalasekera is a Senior Lecturer in Thermo-fluids in The Wolfson School of Mechanical and Manufacturing Engineering of Loughborough University. He obtained his Ph.D. from Imperial College of Science Technology and Medicine. He is currently engaged in combustion, CFD and radiative heat transfer research. He is a Chartered Engineer, member of the IMechE, ASME and the Combustion Institute (British Section). Dr. Malalasekera has a substantial national and international reputation supported by many publications in the field of CFD, combustion and radiative heat transfer.

Dr. Malalasekera is joint author with Henk Versteeg on the CFD text entitled "An Introduction to Computational Fluid Dynamics: The Finite Volume Method", a self contained text covering fundamentals of CFD and advanced topics such as turbulence and its modelling and details on combustion modelling. Since its publication in 1995 it has been reprinted twice and become a popular text among novice CFD users worldwide.

Professor Loveday, together with Mr. Versteeg and Dr. Malalasekera, will be responsible for the modelling of the thermal, flow and mass exchange processes within the proposed project.

Dr. J Scott Turner: Dr. Turner is the leading American termite entomologist and the world expert on *Macrotermes michaelsenii* mound construction and morphogenesis. Author of 'The Extended Organism: The Functional Biology of Animal-Built Structures' and residing at the State University of New York College of Environmental Science & Forestry, he is one of only a handful of people who have studied *Macrotermes* sufficiently to be able to develop a 'tidal flow' model for homeostasis. Dr. Turner will be directly involved in this research and will be overseeing the early stages involved in the capture of 3D mound geometry. He has contributed to this proposal and is setting up research opportunities in the USA for this area. He will be responsible for the selection of the mounds to be studied, as well as supply data on the environmental conditions for the modelling stages of the project.

Collaborating Partners:

The partners listed below, together with the investigators, form the beginnings of a consortium which will be contributing to the research, as well as helping to develop and participate in future proposals. It is intended to initiate annual meetings, of which the first meeting took place in Austin, Texas in the summer of 2002. The collaborators are:

Dr. Johanna Darlington: Dr. Darlington resides at the Department of Zoology at the University of Cambridge. She is acknowledged as having the longest unbroken research career, of almost 40 years, in the study of termite structures, populations and architecture. She is the author of numerous publications and journals and is acknowledged as one of the leading authorities in termite construction techniques in the world. Dr. Darlington will be providing advice, at all stages of this research, and has had active involvement in the formulation of this proposal. Her methods for identification and distribution of biomass within the mound will be used in defining the input variables for the simulation of homeostasis required on this proposal.

Dr. Paul Eggleton: Dr. Eggleton is Head of Entomology at the Natural History Museum (NHM) in London. Dr. Eggleton, along with Dr. Alain Bauman, are specialists in the synthesis of polysaccharides and minerals produced by termites in their saliva. These combine with aggregates to form the construction materials used in homeostatic structures. Of importance to this research will be the understanding and duplication of these binders used to form the mound structure. These materials and their properties, when combined with construction aggregates, must be identified as they are instrumental in producing a permeable structure through which respiratory gases can diffuse and be replenished. It is these data which will form part of the input variables for the simulation of homeostasis which this research will address.

Professor Phill Dickens: Professor Dickens heads the Rapid Manufacturing Research Group (RMRG) at Loughborough University. The RMRG is the largest research group in this field in Europe, will be providing expertise for the reverse engineering elements to capture mound geometry.

Professor Tony Thorpe: Professor Thorpe is Head of the Department of Civil and Building Engineering at Loughborough University and is Associate Dean of Research. His group will assist in the latter stages of the research to explore potential for areas of exploitation of homeostatic function in human construction and habitation.

John Hambley, Paul Prescott and Dr. Alan Hooper: QinetiQ have stated their interest in funding deployable human habitats which might include homeostatic solutions if, and when such technology becomes available and offers commercial viability (Letter of Interest attached). They have emphasised the importance of supporting this pioneering work and of monitoring its progress. In this respect they have offered assistance, where possible, and will be advising on the direction of the research.

PART 2: DESCRIPTION OF PROPOSED RESEARCH AND CONTEXT

1. BACKGROUND

1.1 Introduction

As human populations grow, so too do the needs for innovative methods for building the structures we inhabit. As changes in climate begin to take effect (brought about by unsustainable practices and excessive fossil fuel use), the search is on for construction methods which achieve sustainability; are sparing in the use of materials; and are light in the consumption of energy (Loveday 2003). This proposal outlines research on the integration of structure and function in an animal-built structure which already meets all three of these goals: the mound of the African termite *Macrotermes michaelseni.* These mounds, which are common through subsaharan Africa, are respiratory devices, built from the surrounding soil by the termites in a colony. The mound powers ventilation of the subterranean nest by capturing energy in wind. They are organs of colony physiology, in the broadest sense, shaped to accommodate and regulate the exchanges of respiratory gases between the nest and atmosphere.

The research in this proposal seeks to understand how structure and function are integrated and embodied in the complex architecture of these mounds. The work is intended to answer three broad questions which will serve as both the foundation for future basic research, and as inspiration for more tangible and immediate innovations in architecture, structural and environmental engineering. These questions are:

- What are the detailed architectures which underlie physiological function in termite mounds?
- How do termite mounds integrate and coordinate multiple sources of energy to perform the overarching function of colony ventilation?
- To what extent can the knowledge gained about these phenomena be applied to human construction and hence inform future architectural and engineering construction practice?

This research proposal is high in adventure, vision and multi-disciplinarity, combining elements of mechanical/materials engineering, construction, and entomology, and assembling a team comprised of the world's leading authorities in relevant fields. The proposal concentrates on the biological and engineering aspects of this collaborative effort, to provide a better understanding of homeostasis in termite mounds, the work will point the way towards further research which may eventually lead to new sustainable approaches for human habitation and construction.

1.2 Structure and Function in the Mounds of *Macrotermes michaelseni*

The key to realising this proposal's objectives lies in mimicking and adapting the geometry found in the mound structures produced by colonies of the termite *Macrotermes michaelseni*. These termites have evolved a construction technique which extends the thermo-regulatory, digestive, respiratory and pulmonary systems found within all animals into the structures they inhabit. These structures respond and adapt to constantly changing internal conditions and external weather influences, to maintain an equilibrium in which the colony (which consists of both the termites and the symbiotic fungi essential to the colony's health) can flourish.

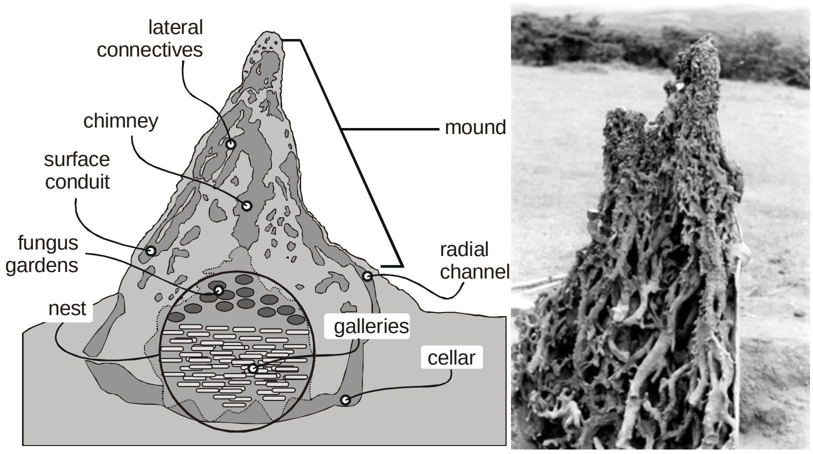

Figure 1. *Left:* Schematic cross-section through a mound of *Macrotermes michaelseni*, showing layout of tunnel networks, nest, and other structures. From Turner 2001. *Right:* Concrete casting of tunnel network of a *Macrotermes bellicosis* nest. From Ruelle 1962.

The termites in a colony do not reside in the mound. The mound, rather, is a physiological infrastructure, built by the nearly one million worker termites residing in the subterranean nest, which contains the hive, nurseries, the royal chamber and the fungus gardens (Bonabeau *et al*, 2001). The mound is permeated by an extensive network of tunnels, which are differentiable into at least three distinct types:

1. The *central chimney*, which forms a large, vertically-oriented void above the nest. The chimney is not open to the outside, but is capped by a porous layer of soil.
2. The *surface conduits*, narrow channels approximately 20-30 mm below the mound's external surface, and which run vertically along the complete height of the mound.
3. The *lateral connectives*, a highly reticulated network of tunnels which connect the chimney and the surface conduits.

Additionally, many termite species, including *M michaelseni*, excavate an extensive underground space, the cellar, whereupon the excavated soil is transported upwards into the mound. When the cellar is present, its air spaces are continuous with those air spaces of the rest of the mound. The cellar may serve also in respiration, and is the site of some remarkable structures. For example, the cellar's ceiling is actually a large base-plate on which the nest is built and which is supported by a solid pillar. As described by Collins (1979), the 'underside of the base-plate bears a series of clay vanes, encircling the plate in a series of spirals. Three or four complete turns of the spiral are common before a break occurs and a new spiral begins. The vane is stalactitic in cross-section, up to 25mm thick at its attachment, 1mm thick and very fragile at the irregularly wavy edge'. These vanes are coated with a white layer of mineral salts, and are presumed by some to promote cooling of the nest (Bristow & Holt, 1987).

The mound is a respiratory organ for the nest, which has a collective metabolic rate in the range of 50-210 watts. The colony's metabolism is supported by a respiration rate roughly equivalent to that of a goat (at the lower end) or to a cow (at the upper end). For many years, nest ventilation was thought to be driven solely by the colony's production of metabolic heat. In this conception, heat and water vapour generated by the nest's metabolism imparts buoyancy to the nest air, lofting it into the chimney. This force then purportedly drives spent nest air downward through the surface conduits, wherein there is an exchange of heat and water vapour with the atmosphere. The refreshed air then sinks down into the cellar, positioned to begin another circuit through the mound.

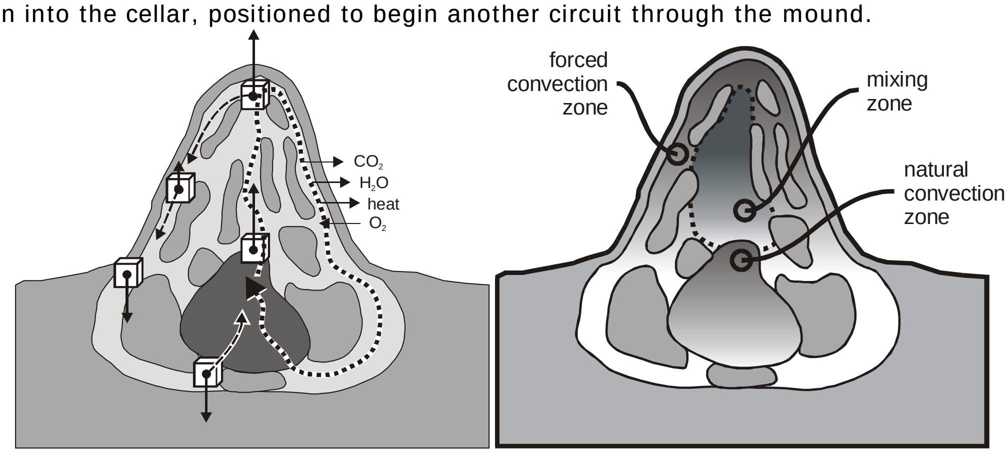

Figure 2. *Left:* "Classic" model of metabolism-driven circulation within a *Macrotermes* mound. *Right:* Updated model of wind-driven ventilation, showing zones corresponding to three phase gas exchange mode respiratory gas exchange. After Turner 2001.

We now know this classical model of nest ventilation is, at best, incomplete. Rather than a circulatory flow, the nest is tidally ventilated, driven by dynamic pressures generated by the chaotic fluctuations of wind speed and direction which are common in the turbulent outdoor environment. As in the tidally-ventilated lung, respiratory gases are exchanged in three phases, each corresponding to a different locale within the mound. Exchange in the surface conduits and chimney cap occurs in a forced convection regime, with flows there strongly driven by wind, analogous to air-flows in the upper bronchi. Exchange in the lower part of the chimney, meanwhile, occurs largely in a natural convection regime. Flows in this region are driven by density variations imparted to the air by nest metabolism: this is roughly analogous to the diffusion-mediated exchanges in the lung's alveolus. Gas exchange in the lateral connectives and middle chimney occurs in a mixed forced/natural convection regime.

Thus, the *Macrotermes* mound does not isolate the colony from its natural environment, as the old conceptions of nest ventilation implied. Rather, the mound intimately ties the colony and environment together, integrating and combining energy from two sources (i.e. metabolism-induced buoyancy and wind-driven pressure) to effect a colony-level function (i.e. ventilation).

Furthermore, the mound is an adaptive interface between these multiple sources of energy for ventilation. Colony function requires not simply ventilation, but regulated ventilation: homeostasis, in a word. As in the homeostasis of the body (a term coined by the American physiologist Walter Bradford Cannon), the overall health of the colony requires levels of oxygen, carbon dioxide and water vapour concentrations to be regulated within narrow limits. This the colony does by matching the rate of wind-induced ventilation exchange to the colony's rate of respiratory gas exchange, brought about through adaptive modification of mound architecture. Thus, an increase in colony respiration which comes from growth, for example, is matched by an upward extension of the mound into stiffer winds that ventilate the mound more vigorously. The *Macrotermes* mound, in other words, is a quintessential example of an adaptive, or "smart" structure, one whose function can adapt to varying demands made upon it.

The mound can be an adaptive structure because it is being continually modified by the colony's inhabitants. At the simplest, individual termites act as conveyors of soil from deep strata, upward onto the mound surface. These movements of soil can be massive, by some estimates about a cubic meter annually per hectare. These *en masse* movements of soil are directed partly by interactions between the myriad termites (and so are self-organized), and partly by large-scale concentration fields of respiratory gases within the mound. Most of the mound's architectural features, for example, can be explained by a simple model in which termites' self-organized soil transport is shaped by 'gaseous templates' laid down by metabolism-generated gradients in carbon-dioxide concentration within the mound. Homeostasis of the nest atmosphere then emerges from a simple "tuning" of soil transport to local variation of respiratory gas concentrations.

Thus, *Macrotermes* colonies provide a natural "model" system which encompasses many of the desiderata, outlined above, for structures that house and provide comfortable environments for people, whether for domiciles or workplaces:

1. They are built by simple and repetitive construction methods from locally available materials, namely assemblages of termites performing local transport and directed translocation of soil.
2. They require little energy to build and maintain. The construction of a typical *Macrotermes* mound involves translocating 1200-1800 kg of soil per year upwards by about 5-10 meters. The work involved amounts to, at most, about 10% of the colony's annual expenditures of energy.
3. They use readily available, natural and renewable sources of energy, namely kinetic energy in wind, to perform a vital function, ventilation.
4. They are compact, and largely self-contained, requiring only inputs of energy in the form of food, sunlight and wind, and without need for export of large quantities of waste. Most wastes are either incorporated into the structure itself, or are fed into an extended system of waste-processing which both extracts energy to support colony function, and culminates in the production of gaseous products which are vented by the same system which handles ventilation.
5. Their function is adapted to the dissipation of energy resulting from the inhabitants' everyday activities.

The immediate aim of this proposal is to undertake a detailed study of the structure which underlies these functions, and to use that structure as a model system for asking fundamental questions about the construction of human habitats. Capturing structure will involve developing methods for high-resolution destructive scanning of parts, or all of a *Macrotermes* mound, which are described more fully below. Once the structure is described, this will serve as a basis for modeling and simulation studies which will address specific questions, including:

- To what extent do variations in architecture of the tunnel networks correspond to, or facilitate, the different functional regimes of gas exchange outlined above?
- How is the kinetic energy in chaotic and turbulent winds captured, damped and integrated with the steadier releases of energy from metabolism, to provide a reliable service (gas exchange) to the structure?
- To what extent can the new knowledge to be obtained about these functions be applied to human-built structures and materials?
- What novel materials and methods of construction (such as those emerging from methods of rapid prototyping) could potentially be developed and ultimately used to construct, service, and maintain

human-built structures which are largely self-contained, self-regulating and self-operating, without recourse to extensive use of materials and external services?

The first two questions are seen as capable of being definitively answered by this research. The last two questions are seen as capable of being answered more speculatively at this stage by the research, hence providing guidance for future research direction.

2 PROGRAMME AND METHODOLOGY

2.1 Aims and Objectives

The aim of this proposal is to develop a better understanding of the structure and homeostatic function of termite mounds, with a view to identifying any lessons which can be learned, and ultimately applied, in human construction and habitation. This, in turn, will lead to a clearer definition of future research directions aimed at delivering some form of homeostasis for human constructions (for example, buildings which are self-regulating and requiring few or no mechanical services systems, and hence much-reduced energy usage).

The project consists of three main objectives:

1) To capture the true 3D geometry of a representative mound of *Macrotermes michaelseni.*

2) To use the geometry as a basis for modelling the flow, heat and mass transfer in the structure, and hence produce a simulation of these processes in termite mounds, validated by measurement.

3) To review the findings and identify potential lessons for human construction methods and habitats.

Successful completion of these objectives will furnish answers to the four questions raised in section 1.2.

2.2 Methodology

This project will be conducted over a three year period. The first objective of the research will involve the scanning and capture of the 'true' 3D structure of a *M. michaelseni* mound. Ruelle (1962) and Turner (2001) have both employed techniques which come close to visualizing and partially capturing termite mound structures. Ruelle's technique (see Fig 1) of filling the mound with a cementiteous slurry, then removing the mound walls with water and trowels, revealed the internal chambers and conduits for the first time as an indication of its complexity. Turner's approach was to take dissections, at 100mm increments, through a mature *M. michaelseni* mound, which were sequentially photographed and traced, to define conduits and internal structure. However, the resolution was too low to identify and define the reticular nature of the structure. Capturing the geometry of a termite mound is now possible using Reverse Engineering techniques. What differs, in this case, from most scanning techniques is that we will be capturing both the outside and the inside of the structure. Techniques such as Magnetic Resonance and Computed Tomography Imaging can scan both external and internal detail but must also be ruled out, in this case, as they are neither portable or cost effective in this application. The solution is the 'slice and scan' procedure demonstrated in projects such as Visible Human®. The process works by the sequential milling and digital photographic scanning of thin layers of a component. It has been calculated that a mature mound, at 3000mm high and 2000mm diameter, will require slices at every 1mm in order to obtain sufficient resolution of the internal structure. Below this thickness, the amount of data produced would be high, due to the cross sectional area of each scan taken, producing around 3,000 scanned images. The images will then be reconstructed using the same technique employed to reassemble 'cryosliced', CT or MRI scan data to form a 3D model of anatomy.

The second objective of the research involves using the captured geometry to develop and demonstrate a simulation model to describe the thermo-regulatory and respiratory gas exchange equilibrium found in a mound. The input variables, i.e. calculation of biomass (and therefore, thermal and humidity generation), measurement of flow within the structure, permeability of the structure to respiratory gases and external weather conditions will be both measured and calculated from the body of knowledge already recorded for these structures, prior to the commencement of scanning. The model will show the process of homeostasis in a static structure (if conditions vary, termites will re-build the structure to re-establish the equilibrium).

The third objective will be addressed by careful review of the findings obtained by the assembled team of investigators and collaborators, together with invited specialists from the UK and overseas in the fields of construction, manufacture and human sciences. This will culminate in the bringing together of these experts for a 'brainstorming' workshop. Here, the project findings and their reviews will be discussed, and lessons identified for potential further research aimed at assessing the possibility for some form of homeostatic approach for human construction and habitation.

2.3 Detail on Programme of Work and Methods

Work package 1: Review of Literature and Identification of Prior Knowledge

An extensive literature review will be conducted in the areas of construction, entomology and simulation. Key to the success of the research will be the distribution of current data and literature to each of the collaborators, to give each sufficient information to perform their function. The resulting review will focus on termite mound construction techniques (known to differ for varying climatic conditions), human construction techniques and simulation/modelling research of the processes relevant to this project.

Outcome: Status of current knowledge and summary report.

Timing: months 0-6

Work package 2: Design and Build 'Destructive Slice and Scan' Apparatus

A modular, robust, frame structure, capable of spanning a mature mound, will be built in the UK, from which both incremental slicing and scanning apparatus will be mounted. This will be transported, via Cape Town, South Africa to Namibia, where it will be assembled, on site, at the location of the termite mounds. The apparatus will run from portable generators and will differ from the conventional slicing system, which uses a milling cutter head, by utilizing a drag chain principle (due to the lower resolution required) similar to that employed in the quarrying of marble, and allowing large cross-sectional diameters to be cut in one pass. A digital scanner, 'on hire' from Minolta Cameras, will be mounted on the frame to capture each incremental slice. For a mature mound, slicing at 1mm increments may take as long as 1 month (@ 10 minutes per slice/scan). A trench will be dug around the mound so that slicing can continue below ground level to capture the cellar structure.

Outcome: Destructive slice and scan 'field' apparatus

Timing: months 0-12

Work package 3: Identify Suitable Mound Stabilisation Material

The stability of the mound, during slicing, must be addressed to ensure internal walls and conduits do not disintegrate during slicing. Samples of mound sections will be shipped by Dr. Turner, who will be on field study in Namibia in the early stages of the project (there are no pest control issues with *M. michaelseni*), to the UK for infiltration testing using silica and epoxy infiltrants. Ensuring sufficient contrast (when scanning) between the walls of the mound and internal voids will be required. Once infiltration/stabilisation of the structure has taken place, shuttering will be placed around the mound and a fine-aggregate cementiteous slurry will be pumped into, and around, the structure.

Outcome: Identification and implementation of a soil stabilisation procedure

Timing: months 0-10

Work package 4: Perform 3D Capture of *M. michaelseni* Mound Geometry

Namibia has been selected, on the advice of Dr. Turner, for its abundance of *M. michaelseni* mounds. He has conducted field trips to a location near Windhoek and has good contacts with local farmers who will allow access to their land for the study. A team of four will be required for the research which includes the technician, the key researcher and Drs. Soar and Turner. The equipment required will be flown to Cape Town S.A., as the closest international airport. This will include the slice and scan apparatus, cardboard shuttering cylinders, soil stabilisation materials, pumps, camera equipment and computer capture equipment. These will be loaded onto a truck with a small digger, which will form the trench around the mound.

Outcome: 3D captured geometry of *M. michaelseni* mound

Timing: month 13-14

Work package 5: Assembling Scan Data into 3D Geometry

There are 3 routes by which the datasets, for the 3000 slices, will be assembled into a 3D model, which include; grey scale edge definition, threshold definition (using Geomagics software) and image and segmentation techniques developed for the Visible Human project®. As with the Visible Human project® there will be separate elements to the mound (i.e. nest, chimney, surface conduits etc.) which must be identified from the model. In addition, 1mm resolution will leave a degree of 'stepping' within the geometry which will require 'smoothing' to ensure a comparable surface to the tunnels and conduits which make up the geometry. This will be achieved using 'smoothing' software/hardware techniques (e.g. SensAble Phantom).

Outcome: 3D model of *M. michaelseni* mound

Timing: months 15-18

Work package 6: Definition of Input Variables to Homeostasis Simulation

The input variables will include: measurement of physical properties of mound material and their permeability to respiratory gases; measurement of ambient conditions within and outside the mound and nest; quantification of cumulative generation (typically from 2 million termites in a mature mound) of exhaled respiratory gases and water vapour, from physical activity, which add buoyancy to the gases that are known to drive homeostasis within the structure. There is no prior work in the simulation of homeostasis as the geometry of the mound has never before been captured, but there are analytical models (Darlington, Korb and Turner, as well as Lüscher (1961), Collins (1979) and Wilson) whose input variables have been carefully measured in mounds. These include: the movement of methane tracer gases around the structure, the measurement of CO_2 levels at key points within the structure; measurement of humidity and water vapour levels around the structure; and most importantly, the effects of external influences such as thermal cycling of the sun, rain and the effects of wind movement, at key points which influence the diffusion of respiratory gases through the walls of the mound. These data will be assembled, together with new data recorded as necessary. Input will come from Professor Loveday, Mr. Versteeg, Dr. Turner and Dr. Darlington.
Outcome: Definition of Input Variables
Timing: months 0-18

Work package 7: Modelling and Validation of Homeostasis
The objective of the simulation will be to demonstrate an equilibrium, or steady state, in which the temperature and humidity and O_2 and CO_2 levels within the nest remain within predefined limits whilst external climatic factors such as temperature, precipitation and wind speed, are varied within certain bounds. The finite volume method will be used to construct quasi-steady models of the heat, mass and momentum transfer processes within the termite mound to analyse the temperature distribution and flow of gases within the structure. The results of WP6 will provide estimates of the main source and sink in terms of heat, fluid momentum and chemical species, as well as estimates of the external boundary conditions imposed on the mound. Detailed measurements on samples of mound material will be made to determine key transport properties such as, the resistance to air flow, thermal conductivity, diffusivity of respiratory gases, radiative surface emissivity, etc. The team of investigators and collaborating partners will regularly interact to share information relating to these and other model parameters which cannot be readily measured or quantified. Where necessary, the effect of variations, in assumed values parameters, will be explored through a sensitivity study with the eventual model. Validation and confirmation of the robustness of the ultimate model will be carried out in conjunction with Drs. Darlington, Eggleton, Korb and Turner, with changes being fed back to refine the model. Professor Loveday, Mr. Versteeg and Dr. Malalasekera will be involved in this process.
Outcome: A validated simulation-based model for homeostasis in termite mounds
Timing: months 19-36

Work package 8: Potential for exploitation of homeostatic function in human construction and habitation.
Any potential lessons which can be learnt for human construction and habitation will be uncovered and considered through careful review of the findings obtained from WP's 1-7, in light of particular expertise. This will be carried out by the team of investigators and collaborators on the project, together with invited specialists from the UK and overseas in fields which include construction, manufacture, materials, building services systems and human sciences. These key experts will be assembled for a two day workshop which will include presentations of the project findings as well as, other relevant research by attendees. It is our intention to promote a forum for active discussion in order to identify the opportunities and limitations of a homeostatic approach for human construction and habitation. Topics will include:

- "Nature-inspired" architectures geared to understanding the static structural attributes which underlie the mound's function by incorporating them into essentially static human-built structures;
- "Smart" architectures which mimic the adaptive architecture of termite mounds, including building sensory networks into structures which control ducting, heating and cooling, or structures which can be built, maintained and continually modified by assemblages of robotic termites;
- Advanced construction techniques based on large scale freeform fabricating machines, able to reproduce very complex external and internal geometry;
- Potential to eliminate mechanical services systems from buildings;
- Interaction of humans with their habitats.

Outcome: A report which assesses potential for exploiting homeostasis in human construction and habitation, and identifies future research directions.
Timing: months 24-36

5 TAKE-UP AND DISSEMINATION

This multi-disciplinary and adventurous nature of the research will draw in elements from many academic disciplines, across which, at refereed international journal publications will be produced. Discussions are being held with the BBC Natural History Unit regarding the possibility of using this procedure to reveal termite and leaf cutter ant mound structures for the *'Life in the Undergrowth'* series, planned for 2005, and presented by Sir David Attenborough. Dissemination will occur through conferences, seminars and articles for the broadsheet press, 'New Scientist' or 'Scientific American'. It is hoped that the major findings, may be suitable for publication in 'Science' or 'Nature'. As with the Visible Human project ®, the data set, generated from the project, will be unique and may generate follow-on research associated with 3D simulation. A workshop is planned, to clarify the potential and direction which this research could take, as well as identify areas of IPR exploitation, which will also act to expand the Consortium onto an internationally recognised platform. Each member will be required to bring additional funding opportunities to the research. Dissemination began in March 2003 with Dr. Soar being invited to give seminars in this research field at the University of Southern California and the State University of New York College of Environmental Science & Forestry.

6 JUSTIFICATION OF RESOURCES

Three posts will be required for this research and will be divided between three areas of work. The first position is for a technician, required for the first 18 months of the project. They will be responsible for the design and construction of the destructive scanning equipment required to capture the mound geometry (WP2). Equipment is commercially available, for components up to $0.5m^3$, from CGI Corp. USA who will be assisting in the construction of the machine described in this research. The technician will be responsible for executing the scanning procedure in Namibia (WP4) and will have joint responsibility, with the Post Grad position, for data reconstruction and geometry smoothing, prior to the simulation stages (WP5). The second position is for a full time Post Graduate researcher. This position will have responsibility for: the literature analysis (WP1); the design, sourcing and procurement of the various elements of the scanning equipment (WP2); research and identification of a methodology for soil stabilisation (WP3); measuring the permeability of the mound structure from samples taken in the field (WP4); assisting the technician for WP5; producing the physical models which will assist in the validation stages (WP7). The final role will require a full time Post Doc position with a track record and expertise in heat, mass transfer and CFD modelling. The role extends through the duration of the project, beginning with the identification of a modelling strategy which is suitable for the research. Extensive research will be required to constrain the input variables, as required by the modelling procedure. They will work closely with the collaborative partners to draw on their own measurements and observations in the field to assist in the refinement of the model and will draw on partner's existing models for homeostasis. Finally, they will be responsible for the dissemination of the research, as well as the organisation and coordination of partner meetings. Funding is required for the workshop which will bring together leading experts and identify future potential and directions (WP8 will be organised by the researchers and the investigators). Details on items of equipment are listed in the costings statement.

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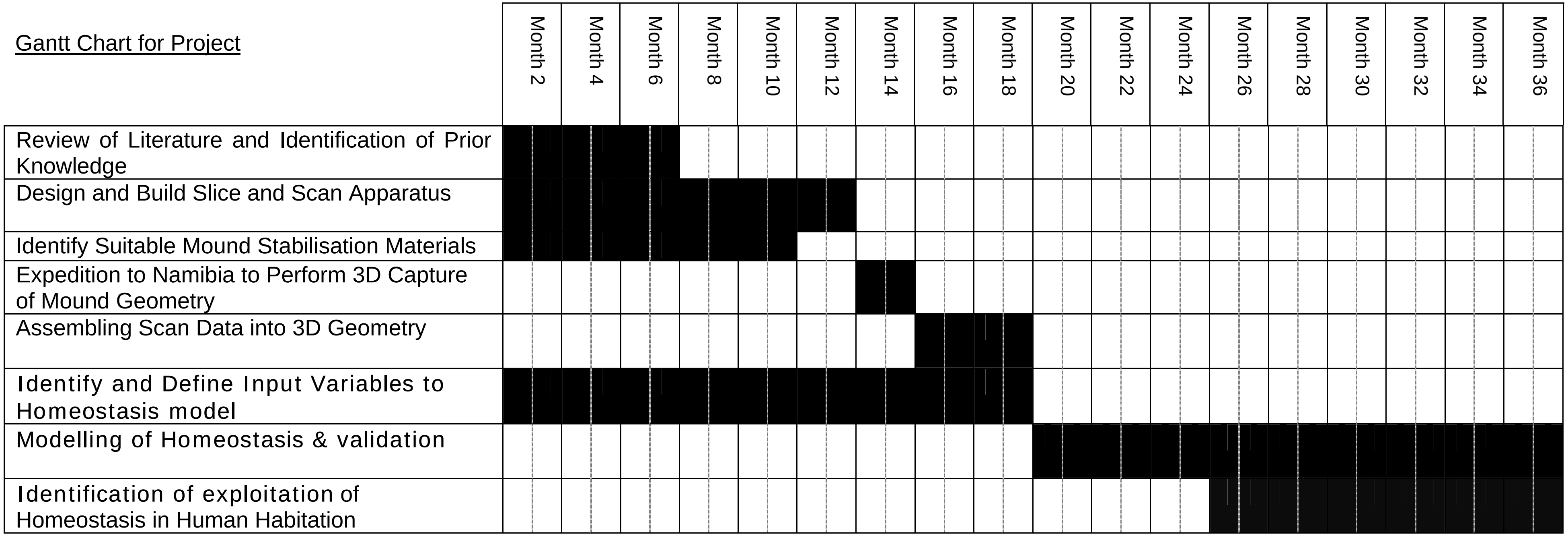

Deliverables

Dr. Rupert Soar will be responsible for overall project management. Review meetings between the collaborators and researchers will be held every 6 months. Internal meetings will be held every 2 weeks. Dr. Rupert Soar will produce quarterly statements of project progress.

D1 Review Reports to include progression of the research and findings up to which point produced in 6 month increments throughout project.

D2 Current State of the Technology Report to form the background to this research as well as bring the researcher employed on this grant up to speed on the subject area (end of month 6).

D3 3D model of Macrotermes mound (end of month 18).

D4 Model of respiratory homeostasis in Macrotermes mounds (end of month 32).

D5 Implications for homeostasis in human habitation report (end of month 34).

D5 Final Project Report (month 36).