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Ground robotic measurement of aeolian processes

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Abstract

Models of aeolian processes rely on accurate measurements of the rates of sediment transport by wind, and careful evaluation of the environmental controls of these processes. Existing field approaches typically require intensive, event-based experiments involving dense arrays of instruments. These devices are often cumbersome and logistically difficult to set up and maintain, especially near steep or vegetated dune surfaces. Significant advances in instrumentation are needed to provide the datasets that are required to validate and improve mechanistic models of aeolian sediment transport. Recent advances in robotics show great promise for assisting and amplifying scientists' efforts to increase the spatial and temporal resolution of many environmental measurements governing sediment transport. The emergence of cheap, agile, human-scale robotic platforms endowed with increasingly sophisticated sensor and motor suites opens up the prospect of deploying programmable, reactive sensor payloads across complex terrain in the service of aeolian science.

This paper surveys the need and assesses the opportunities and challenges for amassing novel, highly resolved spatiotemporal datasets for aeolian research using partially-automated ground mobility. We review the limitations of existing measurement approaches for aeolian processes, and discuss how they may be transformed by ground-based robotic platforms, using examples from our initial field experiments. We then review how the need to traverse challenging aeolian terrains and simultaneously make high-resolution measurements of critical variables requires enhanced robotic capability. Finally, we conclude with a look to the future, in which robotic platforms may operate with increasing autonomy in harsh conditions. Besides expanding the completeness of terrestrial datasets, bringing ground-based robots to the aeolian research community may lead to unexpected discoveries that generate new hypotheses to expand the science itself.

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Keywords

Aeolian processes; Field measurements; Legged robot; Instrumentation; Sand transport; Dust emission; Shear stress partitioning; Reactive planning

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Review Article

Ground robotic measurement of aeolian processes

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Contents

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1. Introduction

Erosion, transport, and deposition of sediment by the wind (aeolian processes) occur in a variety of environments (Fig. 1), including the coastal zone, semi-arid and arid regions (e.g., cold and hot deserts), and agricultural fields in many climates. Aeolian processes also occur on some planetary bodies, notably Mars and Saturn's moon Titan. Common features of these environments are a sparse or non-existent vegetation cover, a supply of fine sediment (clay, silt, and sand size), and winds with sufficient persistence and velocity to entrain and transport the sediment.

Measurement of the rates of sediment transport by wind, and the environmental controls of the processes, are the basis for empirical and theoretical models of aeolian processes, which are designed to predict rates in different locations or boundary conditions (Barchyn et al., 2014). Predictive models can provide important resources for environmental management such as: the amount and type of vegetation required to stabilize coastal and inland dune systems (e.g., Okin, 2008); dust emissions and wind erosion from cultivated and non-cultivated areas (e.g. Leys, 1999); human health, including dust emissions in relation to surface soil characteristics and wind speeds (e.g. Gillette and Chen, 2001); climate modeling via aerosol loading of the atmosphere; and effects of future climate change (e.g. Mahowald, 2007).

Quantification of key variables such as wind speed, shear stress, and sediment properties (e.g. particle size) that determine transport rates is needed in order to fully understand the physical mechanisms involved and to develop predictive models that relate rates of processes to key variables, such as wind speed and surface conditions (Kok et al., 2012). Model parameterization and verification are also dependent on measurement of input and output variables.

Recent reviews (Barchyn et al., 2014; Bullard, 2010; Pelletier et al., 2015) have highlighted the mismatches in scale and precision that exist between measurements and models in aeolian research and geomorphology in general. For example, models for saltation transport rates generally assume constant conditions in time and space, whereas field data highlight the temporal and spatial heterogeneity in transport rates (Sherman et al., 2013). Field data generally provide information for specific events and locations, yet global models predict mean or seasonal conditions over wide areas. Field measurements have been conducted using a variety of instrumentation, so inter-comparison of experiments is often difficult, highlighting the need for standardization of

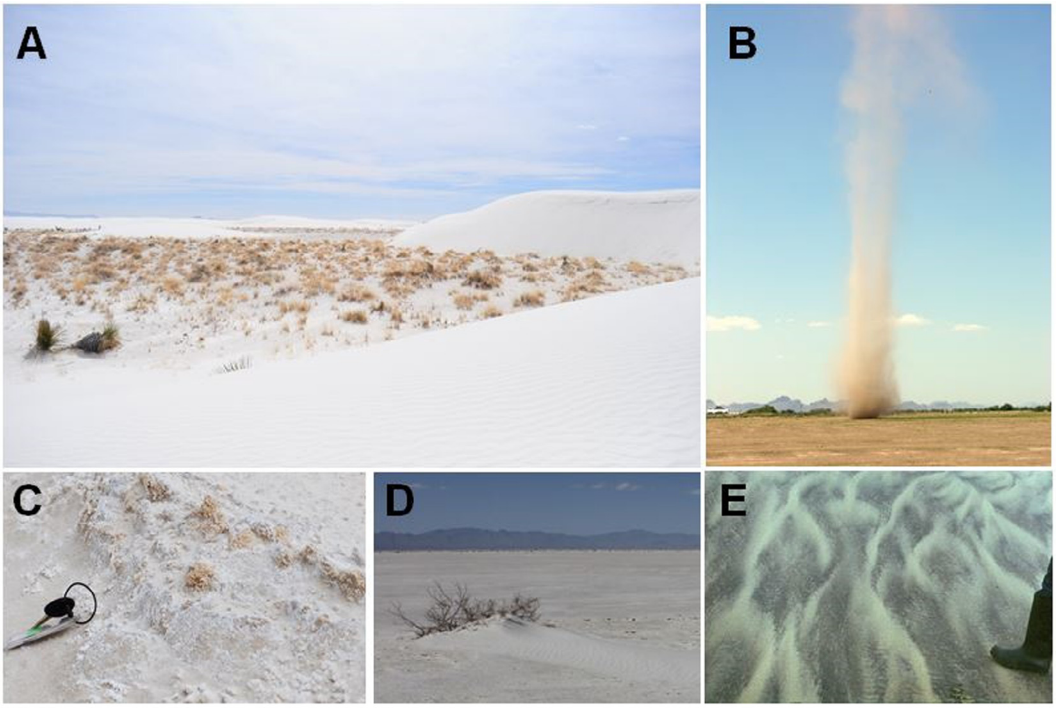

Fig. 1. Aeolian processes and terrain characteristics that are highly localized in space and time. (A) Varied terrain of a dune and interdune at White Sands NM. (B) Dust devil in Arizona. (C) Developing soil crust at White Sands NM; car key for scale. (D) Sand accumulating downwind of a ~1-m diameter shrub at White Sands, NM. (E) Aeolian sand streamers on the Tana River Delta, Norway; boot for scale. Credit: (B) NASA web page & source file, Public Domain, https://commons.wikimedia.org/w/index.php?curid=5585657; (E) Roger Suthren., virtual-geology.info; all others from authors.

methods (Barchyn et al., 2011). These issues underscore the importance of increased temporal and spatial resolution from field measurements, conducted using consistent methods, in order to verify and test predictive models of aeolian processes. This challenge presents a compelling opportunity for robotics to provide novel instrumentation platforms for aeolian science as well as to drive advances in terrestrial locomotion science. Emerging insights from cognitive science then offer to properly align the new sensorimotor capability with the measurement needs and broader goals of aeolian science (Shipley and Tikoff, 2016; Shipley et al., 2013).

In this paper, we explore the challenges and opportunities for developing ground robotic platforms for desert research adapted to operate within the physical environment and conceptual structure of aeolian science. Current stationary modes of measurement offer high at-a-site temporal resolution in, e.g., wind turbulence and saltation flux, but are limited in spatial coverage. Mobile robotic platforms are presently complementary; their advantage lies in the ability to produce spatially-resolved measurements that are also reactive to on-the-ground conditions. Such machines can already help aeolian scientists begin to automate the process of standard data collection. In the long run, coordinated groups of cheap, robust mobile robotic instrument packages hold the potential to greatly increase both the spatial and temporal resolution of aeolian data collection and may develop sufficient autonomy to operate in-situ during the most intense episodes of wind and sediment movement under conditions far too uncomfortable and dangerous for human presence.

2. Field measurements of aeolian processes – current status and challenges

Field measurements of aeolian processes involve quantification of driving and resisting forces. Driving forces generally consist of the available wind energy, while resisting forces may include surface characteristics such as micro-scale roughness, particle size, the size and distribution of non-erodible roughness elements such as vegetation or rocks, moisture content, and crusting and cohesion. The interactions between wind energy and surface characteristics, modulated by topography (as in the case of dune landscapes), determine the threshold wind speed for particle entrainment and the rate of sediment transport.

2.1. Spatio-temporal resolution of erosivity measurements

Existing field measurements show that rates of sand transport and dust emissions vary in time and space at meter and second scales as a result of variability in the wind field (e.g. gusts), topography (especially in dune landscapes), and presence of roughness elements, as well as the condition and composition of the surface. However, most predictive models assume uniform invariant conditions (Kok et al., 2012). Airflow is turbulent over a range of spatial and temporal scales and also responds to changes in surface roughness and topography (e.g. dune slopes), leading to the development of internal boundary layers in the streamwise direction (Baddock et al., 2007). Spanwise variability gives rise to coherent structures and sand streamers even on seemingly homogenous surfaces (Sherman et al., 2013). In addition, surfaces affected by aeolian processes are often of limited extent, resulting in boundary layer transitions (e.g. from interdune to dune; vegetated to unvegetated surfaces) and streamwise fetch effects (Jerolmack et al., 2012). Interactions between airflow and non-erodible roughness elements (vegetation, rocks) at different scales add further complexity (Wolfe and Nickling, 1993), as wind shear stress is partitioned between the surface and the roughness elements. Characterizing turbulent stresses, the resulting bursts in transport and the consequences for dust emission requires high-temporal resolution measurements. A standard field setup involves an array of stationary devices including: sonic and/or cup anemometers; saltation flux devices such optical gates, impact sensors or traps; and dust collectors or optical dust sensors (Fig. 2). Modern setups are allowing researchers to close the gaps in our understanding of how atmospheric turbulence drives aeolian transport. Our understanding of the development and dissipation of boundary layers lags behind, however, because stationary setups offer measurements that are intrinsically well time-resolved (one set of instruments delivers measurements down to the smallest ~1 s timescale of interest) rather than spatially-resolved (multiple sets of stationary instruments are required to achieve spatial sampling at any scale). Hence, because sample numbers tend to be small given a fixed budget of stationary setups, the temporally well-resolved flows around some few vegetation elements, generally cannot achieve both high spatial frequency and useful spans of distance.

In contrast, the same setup deployed on a mobile base offers the prospect of intrinsically well spatially-resolved measurements (taken at arbitrarily dense points along its continuous motion profile) at the expense of temporal resolution. This heretofore unavailable alternative dimension of data collecting methodology seems well worth exploring for aeolian science. For example, it may be desirable to obtain measurements around a large number of elements during a period of relatively uniform wind flow in order to build empirical relations necessary to characterize form drag. Ultimately, the greatest benefit to aeolian science would be achieved by mixed arrays of coordinated mobile and stationary instrument packages.

2.2. Spatio-temporal resolution of erodibility measurements

In addition to the above effects on the erosivity of the wind, there are also spatial and temporal variations in the erodibility of the surface, often parameterized by the threshold wind velocity or wind shear stress (Kok et al., 2012). These can include vegetation cover at different temporal and spatial scales (Hesse et al., 2017), soil moisture (Nield et al., 2011), crusting and cohesion (Langston and McKenna-Neuman, 2005), micro-scale roughness (Nield et al., 2013), and clods and other products of agricultural practices (Leys, 1999; Zobeck et al., 2013). The timescales on which these variables change may vary from annual or seasonal (vegetation cover, soil moisture) to hours (surface wetness) and minutes (crust strength and cohesion). While the aerodynamic consequences of vegetation in terms of form drag are reasonably well studied, we are only beginning to characterize the controls on soil erodibility. Consider how easily dry sand flows, and yet with the addition of a small fraction of water we are able to make sand castles (Fournier et al., 2005). Small changes in soil moisture – of a few percent – can have dramatic consequences on soil erodibility, and such changes can occur over very short distances in arid environments (Wiggs et al., 2004); for example, from wet interdune to dry dune in White Sands, New Mexico (Jerolmack et al., 2012). Salt crusts and bacterial mats also have the potential to change the threshold wind speed by several times (Langston and McKenna-Neuman, 2005). Given these confounding factors and others such as grain size, cohesion and plant roots, predicting soil erodibility across a landscape is a distant prospect. But the creation of such an “erodibility map” for arid regions is necessary to identify potential erosion and dust emission hotspots, and to understand how to mitigate these hazards. Currently, measurements of soil erodibility and local environmental conditions that determine it are limited to a small number of sites. This is an area where the ability to collect spatially extensive datasets in a time-efficient manner would produce a step increase in our understanding of aeolian environments.

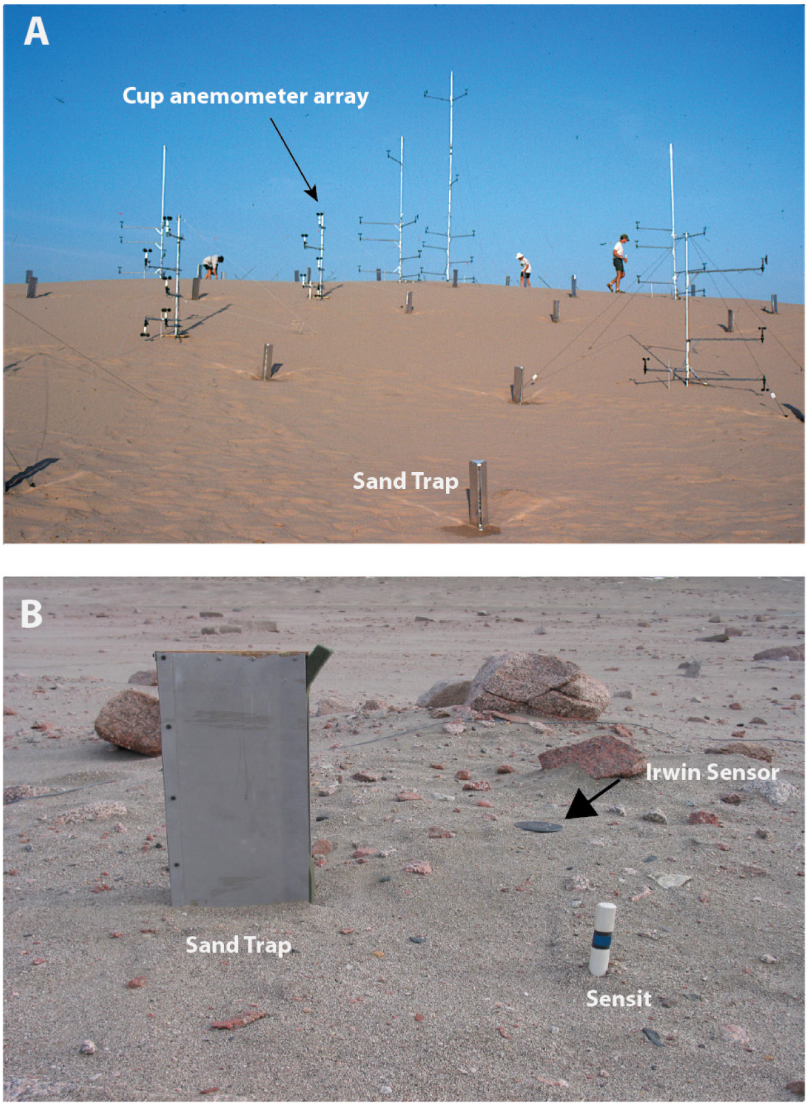

Fig. 2. Examples of the complex setup typical of aeolian field experiments, showing limited spatial/temporal resolution and scale using conventional instrumentation. (A) monitoring of sediment flux using arrays of co-located sand traps and anemometer towers, Salton Sea barchan, 1993. (B) shear stress and sand transport measurements on a rough surface using Irwin sensors, sand traps, and Sensits; Victoria Valley, Antarctica, 2003.

Ultimately, once again, concurrent measurements of sediment transport and surface soil/roughness characteristics are needed to understand the dynamics of the saltation and dust emission systems (Nield et al., 2011) and represent an important challenge and opportunity for aeolian research. The use of terrestrial laser scanning to obtain concurrent data on the saltation cloud, surface roughness, and surface moisture on a drying beach (Nield et al., 2011) provides an example of the potential of this approach. Coordinated groups of mobile sensor platforms have the potential to provide concurrent measurements of aeolian processes and their boundary conditions, by providing the capability to simultaneously sample surface conditions, transport rates, and winds at multiple locations in a flexible measurement protocol.

3. A ground robotic platform for aeolian research

In this section we discuss the present applicability to aeolian research of an extant ground robot, RHex. We begin by summarizing the unique advantages that ground mobility can bring to aeolian data collection. We then introduce the RHex robot as an example of such a platform, and present preliminary results from investigative trips to multiple dune fields, including comparison of scientific data taken by RHex to data taken through traditional methods. This section concludes with a discussion of the novel datasets that RHex is presently on track to help produce.

3.1. Mobile robotic platforms for environmental monitoring

Mobile ground-based robotic platforms have great potential to complement the limitations of fixed instrumentation, and provide transformative datasets to advance aeolian science, similarly to the way remote underwater vehicles (e.g., (Widditsch, 1973; Nodland et al., 1981; Richard Blidberg et al., 1991; Leonard et al., 2007) have helped advance oceanography.

Recent pilot studies (Roberts et al., 2014a,b) highlight the unique capabilities and suggest the associated research opportunities presented to aeolian science by mobile ground robots. First, they can acquire high spatial and temporal resolution field data with no more local surface disturbance and flow interference than a sensor unit in a stationary array, and since they are approximately the size of one sensor unit, they may disturb the environment less overall because they produce flow interference at only

Fig. 3. RHex can traverse a variety of terrains. (A) The XRHex robot. (B) RHex traversing rubble pile. (C) RHex climbing sand inclines.

one location at a time. Second, by attending to the measurements being taken in real time they have the potential to increase sampling density in response to local features of the data (such as high gradients), and thus could maximize observations where they are most needed. Third, payload restrictions often drive technological innovations that have broader benefits. For example, surface soil moisture is commonly measured with a ground-penetrating probe, but new infrared imaging moisture measurement methods currently under development (Nolet et al., 2014; Knadel et al., 2013; Edwards et al., 2013; Yin et al., 2013) could potentially be used by a ground robot to take continuous measurements along the path of travel. Fourth, ground robots can interact with pre-existing surface characteristics and directly measure substrate responses under precise driving forces. For example, measuring the dynamic response force of the substrate (Gravish et al., 2010) under a legged robot can provide a simple measure of soil stability everywhere the robot walks. Taken together, these capabilities may allow researchers to simultaneously assess soil parameters and dust emissions during a wind event and thus provide unique datasets on how the spatial variability in soil erodibility and wind flow affect wind erosion processes and dust transport dynamics.

3.2. An example – the RHex robot platform

Aeolian field work requires high mobility on extremely challenging terrains (deformable sand surfaces, inclinations, etc.). Within the class of ground vehicles, legged vehicles achieve better mobility than wheeled or tracked vehicles in unstructured environments with variable-sized obstacles (Raibert, 1986; Saranli et al., 2001; Raibert et al., 2008; Buehler et al., 1998), and are capable of traversing compliant substrates like sand (Li et al., 2009; Qian et al., 2012). The biologically inspired (Altendorfer et al., 2001) hexapedal robot, RHex (Fig. 3A) (Saranli et al., 2001), in particular, has generated a family of platforms that demonstrate a broad range of mobility competences relevant to aeolian measurement tasks.

Hardened versions of the RHex platform can achieve speeds of 1.5 m/s on flat, solid ground (Galloway et al., 2010), comparable with human walking. These machines have been tested in a variety of environments, including desert terrain (Fig. 3C) (Roberts et al., 2014a,b), environments with obstacles higher than robot hip height (~18 cm) (Fig. 3B) (Saranli et al., 2001), and inclines in the form of hills and stairs (Johnson et al., 2011). Although compliant ground such as dune surfaces present more difficulty (Li et al., 2009, 2010; Qian et al., 2012, 2015; Zhang et al., 2013), RHex can consistently climb sand dunes inclined to 25° (Roberts et al., 2014a), and has successfully climbed sand dunes of up to 29° (Roberts et al., 2014b), achieving the inclination exploration requirement (Gravish and Goldman, 2014) for most aeolian measurement tasks.

In addition to its outstanding locomotive capabilities, RHex also has a convenient, capacious and amply connected and powered payload system that allows for a variety of aeolian sensors to be easily mounted and electrically interfaced with the robot onboard electronics (Galloway et al., 2010). RHex's mechanical mount consists of two parallel Picatinny rails (40 cm long, 14 cm apart) that span the body length of the robot, providing extra space and rigidity for the sensor payloads. RHex's sensor electrical interface includes power connectors capable of delivering various voltages to payloads, as well as multiple USB connectors and an Ethernet port that allows direct connections between payloads and the robot's on-board computer. With such an electrical interface, along with RHex's custom-developed software, *Dynamism* (Galloway et al., 2010), the robot can be used as a data logger to register data inputs from a variety of aeolian sensors. In addition, the current version of RHex supports a payload computer that includes a multi-core programmable GPU. Such computational power enables fast, parallel sensor data processing and allows for event-triggered autonomous measurements discussed in Section 4.

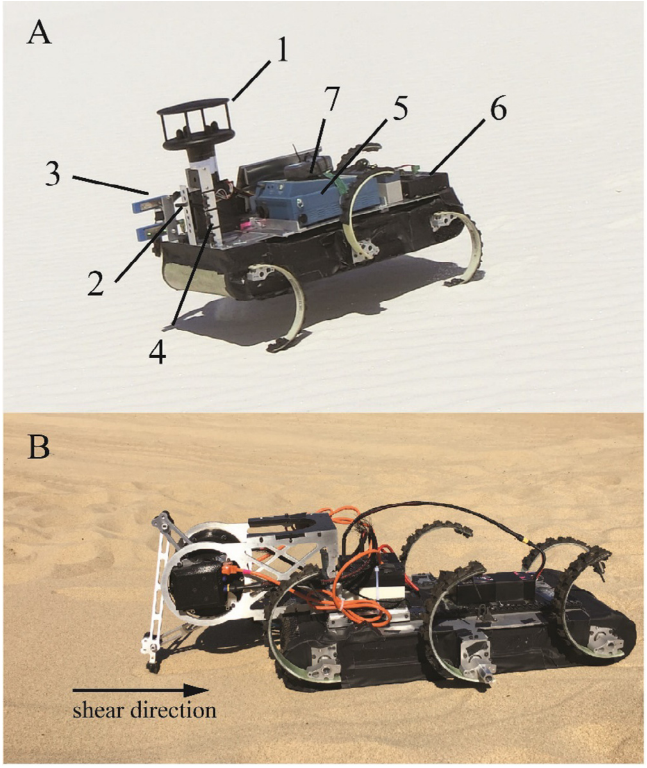

Fig. 4. Sample RHex payloads relevant to aeolian science. (A) Desert Research Institute custom sensor instrumentation on RHex, including 1) Gill 2D WindSonic anemometer; 2) TSI DustTrak 8520 PM10/PM2.5 dust concentration sensor air inlet; 3) Wenglor YH03PCT8 optical gate as saltation sensor 4) DRI custom miniature sensor suite, including saltation sensor and dust concentration sensor (10 kHz); 5) TSI DustTrak 8520 PM10/PM2.5 dust concentration sensor; 6) Datalogger CR1000; and 7) GPS. (B) RHex using an additional (7th) robotic leg deployed as a force sensor to measure shear strength of the substrate. For each shear test, the direct-drive shear leg mounted on RHex's back submerges a few millimeters into the substrate, and then drags a thin layer of grains across the surface while measuring the mechanical shear strength of the substrate.

Another important feature of RHex is its ability to provide uninterrupted power with hot-swap batteries. RHex has two battery bays and each battery is a 10-cell (37V) pack with 3900mAh capacity, which can provide approximately 45–90 min of active run time, depending on the difficulty of the task (Galloway et al., 2010), and up to two hours run time per battery when the motors are not powered. With the battery hot-swap feature, a user can replace discharged batteries with fully-charged ones without any interruption in robot operation. This feature significantly extends RHex's operation time and provides the possibility to operate continuously by connecting two batteries in parallel and replacing one at a time without having to stop or interrupt the field data collection. In addition, RHex is small enough for a human to carry in a backpack (10 kg) while offering a large, flat back (57 × 39 cm) on which a diverse suite of sensors can be mounted (Galloway et al., 2010). Due to its compact size (as compared to other multi-terrain vehicles), RHex's six C-shaped locomotive legs leave very light impact (no more than a few centimeters depth) on the terrain during ground traversal, significantly less destructive in comparison to the impact of fixed stations, thus ensuring that its deployment is relatively free from encumbrance by government regulations.

RHex has been deployed for missions with human escort to test the feasibility of different aeolian sensor configurations (Fig. 4), with data recorded both through the robot's on-board computer (Roberts et al., 2014a) and to data loggers sitting on the robot's back (Roberts et al., 2015; Reverdy and Koditschek, 2016). These feasibility studies report on experience with a varied mix of typical aeolian sensors, including anemometers (2D Gill Windsonic), optical gate sensors (YH03PCT8 Wenglor and Optek OPB800, pyranometers (CS300), temperature and relative humidity probes (CS215), dust instruments (Sharp Dust and TSI DustTrak 8520 PM10/PM2.5); and sensors not typically used for aeolian research, such as laser range finders (Hokuyo UTM-30LX and Velodyne VLP16) and color cameras (GoPro Hero 3).

3.3. Field trials with RHex

3.3.1. Comparison of data sets from RHex with those taken conventionally

Initial field experiments in White Sands and Jornada reported in (Roberts et al., 2014) demonstrate that the data capture rates and variance through the RHex robot are comparable to prior published materials (Figs. 5 and 6). As an example, data sets collected at

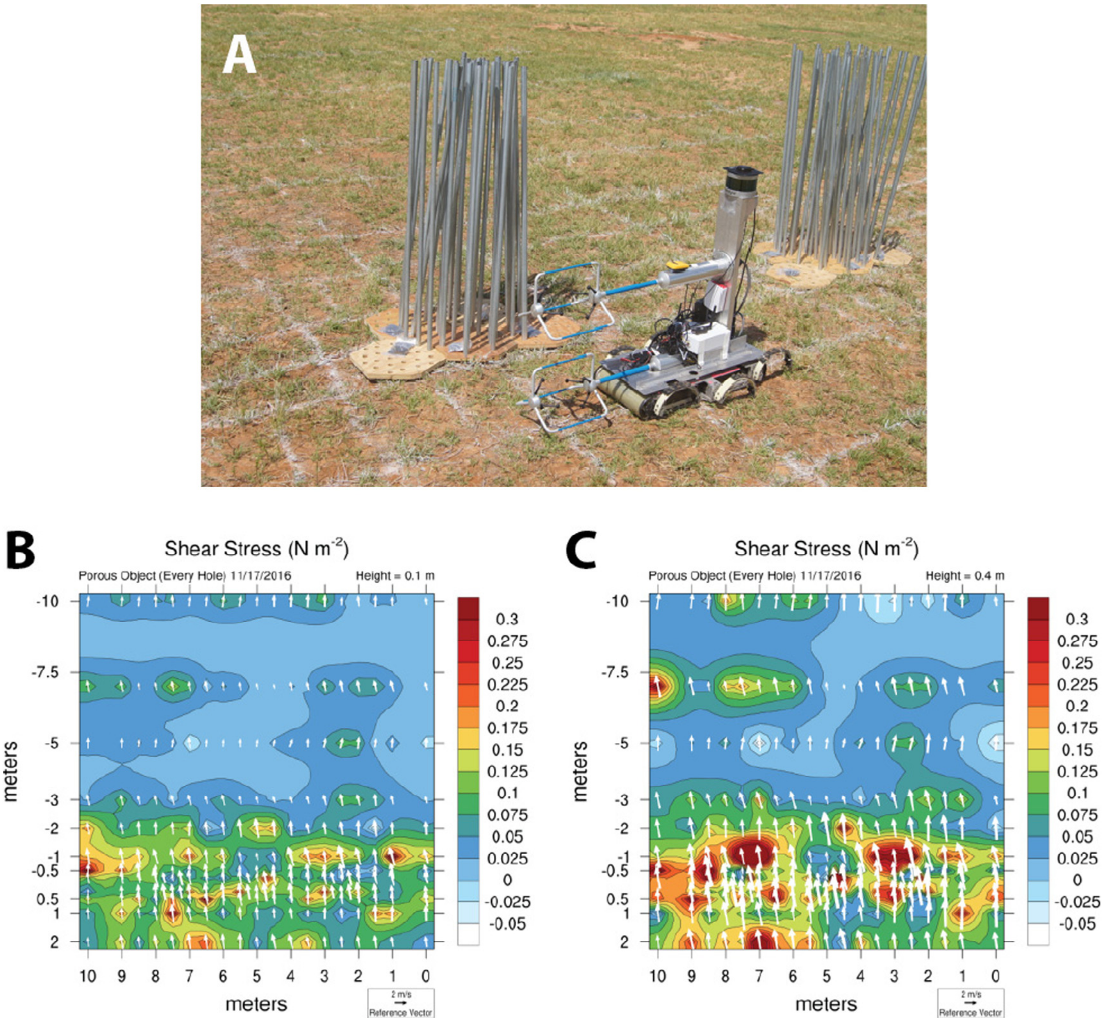

Fig. 5. (A) RHex traversing a grid surrounding replicate artificial porous objects. Instrumentation moving with RHex includes two horizontally mounted sonic anemometers at 0.1 and 0.4 m heights, a digital compass, and, on the top of the mounting tower, a 360° X 15° LIDAR capped with a RTK corrected GPS receiver. Data is logged onto multiple miniature computer boards mounted to and in front of the mounting tower. (B) Wind and shear stress field at height of 0.1 m (C) Wind and shear stress field at height of 0.4 m.

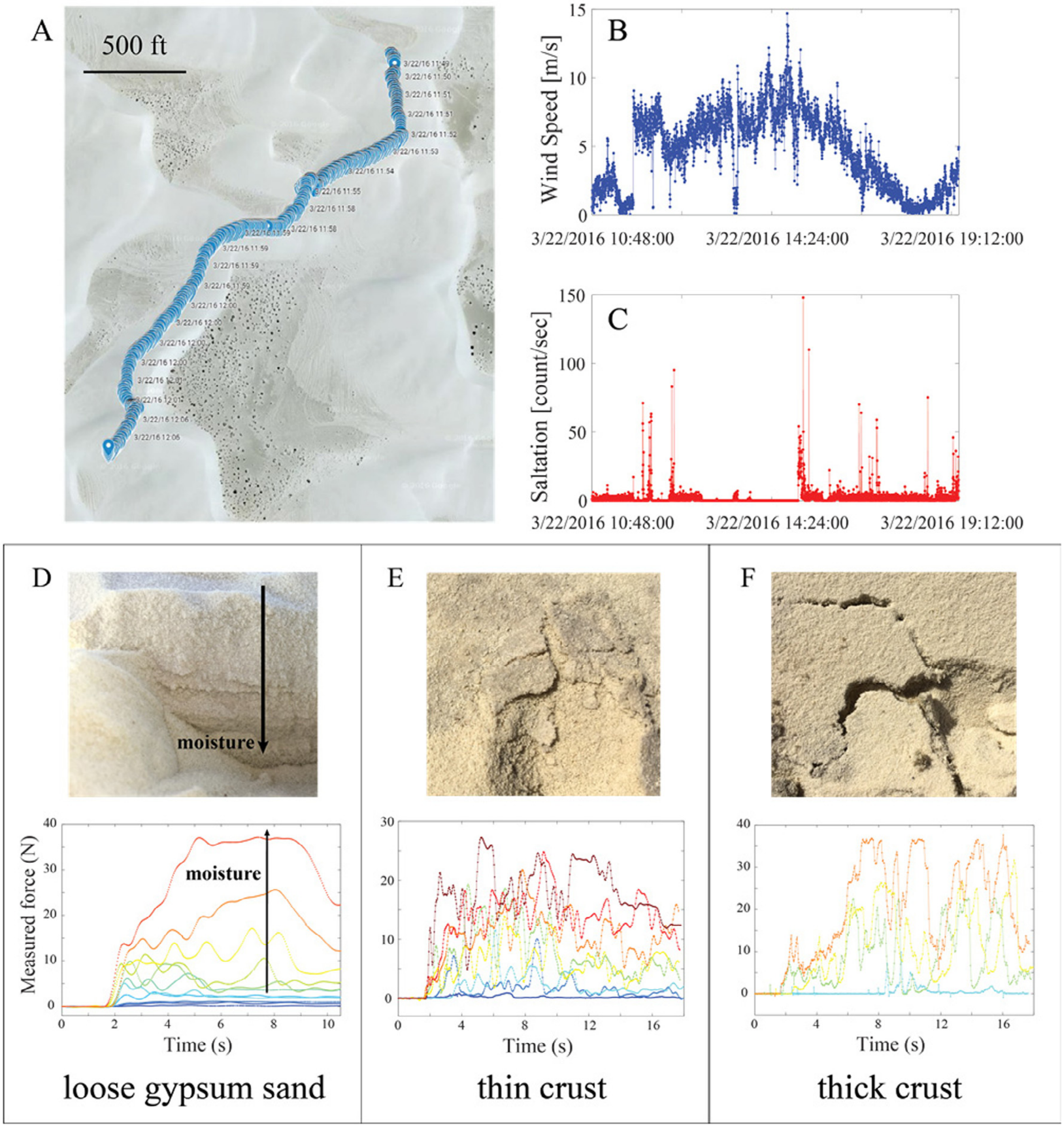

Fig. 6. Initial field trip results that demonstrated the potential for ground-based robots to provide transformative datasets for aeolian science. (A) A sample transect of the robot traversing dune field at White Sands, NM. (B) Wind speed measured by the robot along a long transect including the segment showing in (A). (C) Saltation particle flux rate measured by the robot along a long transect including the segment shown in (A). (D–F) Shear force measured by a 0.028 m wide plate driven by linear actuator at a speed of 0.05 m/s at White Sands, NM. Colors represent the depths at which the shear measurements were performed. In (D) the depths are 0 m (bottom blue curve) to 0.055 m (top red curve) with an increment of 0.005 m; in (E) the depths are 0 m (bottom blue curve) to 0.035 m (top red curve) with an increment of 0.005 m; in (F) the depths are 0 m (bottom blue curve) to 0.015 m (top red curve) with an increment of 0.005 m. Results indicate significant increases in the resistance to erosion with increases in soil moisture (D) and level of bioactivity (E, F). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

White Sands show that high-frequency (1 Hz) variations in wind speed and sand transport rates can be captured by the RHex (Figs. 4A; 6B, C), while moving at low speed (<1 m/s). Precise calibration of these measurements can be achieved via calculation of the robot movement vector speed and direction obtained with the onboard high-resolution GPS. Preliminary data allow estimation of threshold wind speed for sand transport at 0.3 m height using the time fraction equivalence method (Stout and Zobeck, 1997) as 6.57 m/s (event 1) and 5.8 m/s (event 2). Equivalent wind shear velocity estimates using an aerodynamic roughness value of 0.002 m are 0.366 and 0.326 m/s respectively. Field experiments to directly compare stationary and mobile measurements of wind speed and sand transport using RHex with conventional anemometry and sand transport sensors are planned.

3.3.2. Potential for new insights from mobility

Work now in progress toward generating new data for aeolian science from the RHex machines is proceeding in two principal directions. First, we are addressing the general need for increased spatiotemporal resolution that largely motivated the original idea to explore robotics in this domain. Second, we have initiated a specific new effort to characterize soil erodibility and crust strength – i.e., to generate erodibility maps and to empirically determine the environmental controls on the erosion threshold across landscapes.

The sensors we have shown can be used with this robot, either through the robot's computer or through data loggers mounted on its top, to provide state-of-the-art data comparable to prior studies in aeolian science. The mobility of the robot platform provides additional opportunities for experiments that would otherwise be difficult to execute, either due to time or expense. For example, the monetary cost of setting up a dense network of anemometers and saltation sensors over multiple dunes makes such an experiment untenable. In contrast, mounting all desired sensors into one package that can move between desired data capture locations during a wind event reduces sensor cost substantially and enables a previously unforeseen level of spatiotemporal data resolution (Fig. 6A–C). Experimental repeatability is further increased, and variability decreased, by automating data capture based on environmental triggers, such as wind speed or dust emissions. In such scenarios, robotic platforms could be programmed to carry out specific measurement tasks - such as dust emissions or surface soil condition – when wind speeds exceeded a given threshold magnitude, and continue executing until wind speeds decrease and dust emissions cease. We stress that a robot is best conceived of not as a replacement for but rather complementary to stationary modes of measurement. Walking over a dune (or series of dunes/interdunes) during a transport event can provide profiles of near-surface winds, sediment transport rates and soil conditions. But, since winds are time-variable, a stationary setup is needed to characterize regional airflow to provide a baseline for the spatial profile. While spatial data are ideally suited to stationary wind conditions (which never happen), the limitations imposed by time-varying winds may be at least partially overcome in two ways: (1) RHex could traverse a transect repeatedly during a wind event, and these transects could be temporally averaged to reveal spatial patterns; and (2) multiple RHex robots could operate simultaneously.

Ground robots like RHex can directly characterize the mechanical properties of the surface with their legs, thereby obtaining unique field datasets to provide quantitative support and generate new insights for dust emission and transport models. One effort we are presently pursuing seeks to assess soil erodibility through mechanical shear tests. Soil erodibility varies dramatically with changes in grain size, cohesion, soil moisture and crust development. These complex and often co-varying factors limit predictability and require empirical measurements at each site of interest. Traditional measurements usually require cumbersome wind tunnel devices deployed in-situ to determine the threshold shear velocity. Recent studies (Roberts et al., 2015; Qian et al., 2016) in the laboratory and at White Sands National Monument suggested that soil erodibility was strongly correlated to the mechanical shear strength of the substrates (Qian et al., 2016). Therefore, soil erodibility can be quickly assessed in the field by measuring the resistance shear force exerted on an actuated shear plate or a robot leg that is submerged a few millimeters into the subsurface and dragged through a thin layer of grains. Such mechanical shear methodology shows great promise for ground robots to be used for investigation of spatial transition patterns in erodibility. Furthermore, shear strength testing reveals time-varying responses of the substrates during sustained shearing events, and could thus provide insights into the material failure mechanism beyond the threshold point (Fig. 6E, F). Current technology exists to measure grain size (visible light images), soil moisture (infrared images) and salinity (conductivity probe) with small sensor payloads. If a robot such as RHex were equipped with such sensors, it could crawl over a landscape during inactive periods and generate large datasets of soil erodibility and controlling factors. In principle, we have in hand the tools to generate spatial maps of erodibility, and to empirically determine environmental controls on it. We view this prospect to be transformative, and believe that this is a unique capability of a legged robot such as RHex. Finally, in the current setup RHex uses a separate (non-walking) leg that is specifically designed for measuring shear strength by scraping (Fig. 6). In near future this will not be necessary; updates to its sensorimotor capabilities will allow the walking legs themselves to act as rheometers, measuring soil strength with every step.

4. Present and future opportunities for ground robotic measurement of aeolian processes

Aeolian robotics experiments of the kind we have discussed above are most appropriately viewed through two different perspectives related to the time horizon of research: in the short term, the robot can be used as a new tool to collect data of a similar type and quality as existing tools, but with greater spatial resolution; in the longer run it offers promise as a tool to not just passively collect but to actively generate datasets using information about the data already collected and the user's research priorities. The shorter horizon has already arrived: preliminary data from field work reported here begins to document the mobile robot's role as another, more versatile, tool in the aeolian scientist's field kit. But, over a longer term, there are growing signs that similar or superior mobility (Kenneally et al., 2016) will become available in cheaper robotic platforms (Ghost Robotics, 2017), encouraging the use of coordinated groups that, in turn, motivate the need for increasingly autonomous operation.

As we look towards the future and towards robots with more capable autonomy, the need for the robot to be able to learn scientists' priorities becomes more relevant. A field tech trainee begins by performing routine tasks under a scientist's close guidance. As trainees gain skills and understanding, they are granted increasing autonomy to formulate hypotheses of a narrow but useful kind, design experiments of specifically limited scope, and gather data on their own. Similarly, robots may increasingly come to assist in the collection and processing of scientific data, never substituting for but rather amplifying the productivity and capabilities of human scientists (see Fig. 7). We begin by describing routine tasks that robots could automate in the near future, then move on to the possibilities for more capable automation and finally offer some more speculative glimpse of potential future aeolian science workflows.

4.1. Present opportunities for increasing spatiotemporal resolution of aeolian process measurements

In the previous section we have documented the ability to deploy in desert settings a presently extant human-driven robot with a variety of sensor suites that are of interest to aeolian scientists. In our work to date and in the near-term future, we are focusing on developing the capability to automate routine tasks. Our goal is to package the robot into a modestly programmable tool that aeolian scientists could readily adopt and deploy in the field. We endeavor to develop a platform that could be effectively used by most aeolian researchers after a weekend's training session.

Aeolian research historically has used fixed-position sensors, whether for "long-term monitoring" studies in which key variables are measured routinely or for "event-based" studies in which intensive measurements are carried out during periods of high particle movement. Mobile instrumentation packages such as the Portable In-Situ Wind Erosion Laboratory (PI-SWERL) (Etyemezian et al., 2007) can already increase the repeatability of intensive event-based studies, substantially increasing the spatiotemporal resolution of monitoring-style datasets. The availability of (semi-) automated concurrent measurements of surface conditions, winds, and sediment transport provided by RHex and its successors offers the opportunity for new insights into the complex relationships between erosivity and erodibility of desert surfaces.

Established methods from robotics provide a straightforward way to develop simple automation. In the previous section we have documented the ability to deploy in desert settings a presently

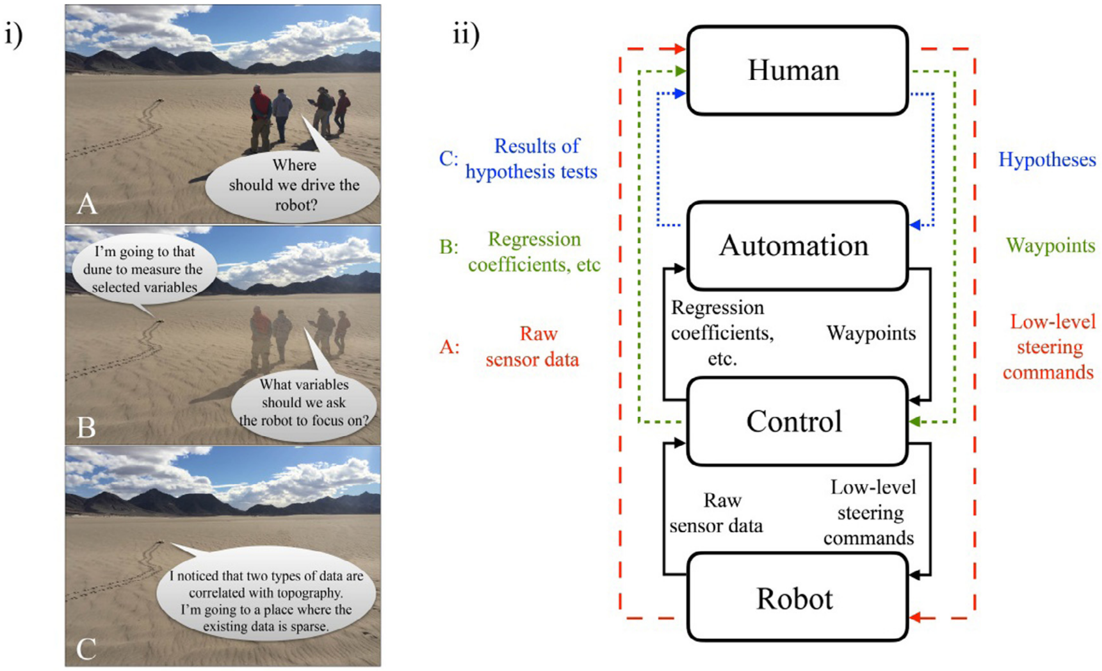

Fig. 7. (i) Conceptual figure showing the near term, intermediate term and long-term science prospects for legged robot science. A: current/near term (spatial profiles, soil erodibility). B: medium term (dynamic reaction to events). C: long term (the field technician). (ii) Diagram showing the information flows associated with increasing levels of automation. Black arrows show flows of information internal to the automated system, while colored arrows show flows between the system and its human supervisor for various levels of automation. A: Current practice (red long-dashed line). Humans provide direct steering commands and receive raw sensory data. B: Implementing established control methods (green short-dashed line). Humans provide GPS waypoints and candidate statistical models (e.g., variables that are believed to be correlated) and receive processed data (e.g., correlation or regression coefficients). C: Implementing novel automation techniques (blue dotted line). Humans provide quantitatively-testable hypotheses (e.g., a linear regression model will fit some set of variables in these regions); the robot generates waypoints, collects and processes data to test the hypotheses, and returns the results of the hypothesis tests to the human. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

extant human-driven robot with a variety of sensor suites that are of interest to aeolian scientists. A natural next step is to leverage existing waypoint-following capabilities to allow the robot to perform measurements along transects defined, e.g., by known GPS coordinates. Slightly more advanced automation would allow the robot to find previously located roughness elements and perform transects to gather data on airflow around them, to perform repeated transects over dune surfaces, or follow dune crest lines. Also achievable in the near-term future are machines that employ a limited sensor suite to detect relevant environmental conditions (e.g., high winds), that then trigger more sophisticated (and energy-intensive) data collection behaviors (e.g., on saltation events) when they are more likely to occur. Such simple reactive capabilities would significantly extend the robot's effective battery life and permit more persistent data gathering. Other methods in the robotics literature such as automating geologic site survey tasks by seeking areas where a reflective spectrometer indicates novel phenomena (Thompson and Wettergreen, 2008; Wettergreen et al., 2014) may also prove relevant.

A mobile robot carrying such a sensor package could measure and react to weather conditions. Appropriate modifications to the RHex charging infrastructure could allow the robot to autonomously dock and charge itself at a solar-powered charging station in the field. With currently increasing battery capacity and solar panel efficiency, this would permit continual autonomous operations of approximately half an hour on followed by an hour and a half off for charging. With such capability, the robot could perform specific "experiments" in response to environmental conditions while on daily hikes with a human companion, or be triggered remotely to perform a series of pre-programmed experimental hikes alone, such as dune transects and long-term monitoring of multiple vegetation elements, in response to favorable weather conditions at the site. This raises the prospect of automating routine measurement tasks which, while not replacing any aspect of the aeolian scientist's workload, adds the capability to collect many more samples under different conditions than would previously have been possible.

Finally, autonomous walking would allow the ability to generate spatially extensive erodibility maps and accompanying soil environmental data. A mobile robot could be programmed to test the soil at fixed intervals in space, but to react to spatial changes in erodibility by increasing sampling frequency in regions of strong variation and decreasing sampling frequency in homogeneous portions of the landscape.

4.2. Future opportunities for autonomous robotic measurement platforms

Looking forward to the sorts of autonomy achievable in the medium- and longer-term future, the robot-as-apprentice metaphor is a valuable guide. Deploying and directing such autonomy may eventually become analogous to training a technician: we would like to teach the robot how to perform a limited scope of scientific decision making. A growing body of human learning science focused on the earth sciences has begun to codify the manner in which previously collected data and the current environmental conditions trigger such questions as what data should be collected and where should it be collected (Shipley et al., 2013). For example, in field mapping, generally experts quickly develop a model of the large-scale geological structure and collect data sparsely as long as it is consistent with the model. Inconsistencies between data and model will result in model revision from new data taken from a broader collection area. Here autonomy might be viewed as a form of automated online experiment design.

The scientific value of data can be used to prioritize data collection recorded (Castano et al., 2003; Kastens and Ishikawa, 2006) and in principle optimization methods may be used to maximize the scientific value of data collected on a given mission, in the same way that marginal value theorem can be applied to foraging with patches that have diminishing returns (Charnov, 1976). One method for doing so emerging from extra-terrestrial robotic exploration is as follows (Castano et al., 2003). The value of data is first defined, e.g., for distinguishing between competing hypotheses (along the lines of a statistical power computation) or in terms of reducing uncertainty in a quantity to be measured. The costs for carrying out an action are then defined, for example in terms of battery life, time required, or risk of damage to the environment or the robot involved in gathering a specific type of data. Standard decision-making algorithms can then be adapted to maximize the value of the generated data while minimizing the associated costs. Note, as is often the case in science, the value of the data is unknown prior to sampling, but once sampling begins an estimate of the value of further data is possible by comparing incoming data to predicted data (Shipley and Tikoff, 2016). The tradeoff between value and cost may change depending on context. For example, if the robot has just begun its mission, it likely makes sense to select conservative maneuvers, while near the end of battery life, it may be sensible to attempt risky maneuvers that might yield commensurately higher value data just before the end of the mission. One way to capture this context-dependent choice is through a preference-based technique (Keeney and Raiffa, 1993), where the robot is endowed with a function that models a human scientist's preferences over possible decisions. This function can be constructed by presenting a scientist with a series of binary queries whose successively recorded decisions express their preference (i.e., in this context, would you prefer to take action A or B?). This concept will be familiar to anyone who has visited an optometrist and expressed preferences relative to a preferred series of pairs of lenses. Similar techniques have recently been used in the underwater robotics literature (Somers and Hollinger, 2016) and are subject of ongoing research.

The nature of the above-mentioned methods has implications in terms of the types of aeolian data collection whose burdens can be mitigated by automation. The more precisely aeolian scientists can articulate their hypotheses, the more effectively automation can be designed to help test them. Where scientific objectives primarily demand more and richer data sets, robots can help gather data more quickly. However, the new automated decision-making capabilities of the robots will be most valuable in contexts where scientists have models that, at least in principle, could be subjected to a quantitative hypothesis test. Such models could be as simple as the understanding that certain environmental variables should explain another one, or as complex as a model predicting the functional form of the dependency among the variables. We suggest that the need for such models may encourage important work in the aeolian research community and welcome dialog with those who wish to engage in modeling work of this kind.

4.3. Perspectives for future work

Current understanding of the spatial and temporal dynamics of aeolian sediment transport and dust emissions is in many cases limited by our ability to measure the relevant processes and parameters on spatial and temporal scales that will enable development and verification of existing and future empirical and theoretical predictive models.

In the future, instrumentation will continue to become more robust, compact, and lighter. Thus, many devices currently too large to include within a robotically deployed instrument package may soon be reworked for integration into the automated data collection streams enabled by autonomous or semi-autonomous robots. Indeed, the advent of such increasingly capable robot platforms may accelerate the development and deployment of more compact and robust sensors, as has happened repeatedly with planetary science missions. Corresponding increases in computational power, new battery technologies, locomotive prowess and the refinement of their capacity for representing the scientific agenda, will surely stimulate growing interest in robotic aeolian field assistants. Ground robots may become common, employed to iteratively measure small landscapes to quantify changes to vegetation, soil surfaces, and topography as they occur, ideally in combination with UAS (as well as traditional suites of fixed instrumentation) for production of high-resolution digital elevation models of topography. We also see great potential for ground robots to characterize and understand spatial variability in erodibility, in particular for use in identifying hot spots for erosion and dust emission. Long-term high temporal frequency measurements, possibly triggered by process thresholds (e.g. wind speed), will greatly increase our understanding of environmental change at multiple spatial and temporal scales. This information could warn land managers of impending degradation and allow for management decisions that would protect the environment and increase sustainability of agroecosystems in drylands. In turn, growing understanding of the cycle of data collection and scientific model revision will guide the development of new computational frameworks to support such scientific and policy decisions.

Truly useful advanced autonomy for robotic aeolian laboratories will require a deep collaboration between three distinct groups of researchers: aeolian scientists, cognitive scientists, and roboticists. Aeolian scientists must guide the process by defining the scientific objectives and the hypotheses they would like to test. Automating the scientific process will require representation of the aims and understanding the mechanics of the decision-making process, which requires cognitive scientists. Finally, robotic science and engineering will be required to implement these capabilities in reliable physical platforms.

The introduction of advanced robotics and automation will undoubtedly change the process of doing aeolian science. To guide us in managing this change, we can look to the experience of oceanographers and space scientists, who have contributed to and benefitted from such advances in recent past decades. In developing such tools for the aeolian community the appropriate goal is not to replace people in the scientific process, but rather to help them to be more productive. The benefits of new and more comprehensive data sets will be transformative, leading to new analyses and insights, greater understanding of processes, and new predictive models.

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