A Biomimetic Approach to Robot Locomotion in Unstructured and Slippery Environments

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Abstract
While much attention has been given to bio-robotics in recent years, not much of this has been given to the challenging subject of locomotion in slippery conditions. This study begins to rectify this by proposing a biomimetic approach to generating the friction required to give sufficient propulsive force on a slippery substrate. We took inspiration from a successful biological solution—that of applying hair-like structures to the propulsive appendages, similar to the setae found in nereid polychaetes living in muddy habitats. We began by examining the morphology and the mean locomotion parameters of one of the most common nereids: Nereis diversicolor. Following this study, we designed and fabricated a robotic system with appendages imitating the biological shape found in the worm. A flexible control system was developed to allow most of the locomotion parameters observed in the real worm to be applied to the robot. Experiments on three different natural substrates ranging from fine sand to gravel showed that, whereas a plate attached to the appendage generated most thrust on a small particle substrate, a bundle of artificial setae attached to the appendage generated most thrust on a large particle substrate. On all types of substrate tested, an appendage without any attachment did significantly worse than one with. This suggests that hair-like structures can be advantageous.

Keywords: bio-robotics, biomimetics, polychaeta, thrust generation, friction

1 Introduction
The field of robotics has in recent years been looking more towards animal locomotion. While the wheel remains the optimal solution for locomotion on flat level surfaces, biologically-inspired robots are being developed for locomotion on more structurally complex terrains. The hexapod design inspired by insects is the most promising one for fast locomotion on rugged terrain[17]. The cockroach, especially, has been used as a model organism for several biomimetic studies, ranging from mechanical parameters[22] via leg sensors and design[23] to control[4].

However, despite the increased attention on bio-robotics, most research has focused on locomotion over firm ground, as described above, or on underwater locomotion[25-27]. Scant attention has been given to locomotion in tortuous and slippery environments, such as muddy terrain, sewage pipes and organic environments. An example of the latter that has substantial biomimetic potential is locomotion inside the human body. Current endoscopic practice consists of pushing relatively stiff structures through the body cavities. This procedure can cause considerable discomfort to the patient. Steps are, therefore, currently being taken to develop self-moving endoscopes both by employing a traditional engineering approach[28] and by using a biomimetic approach[25,16]. Both approaches, however, suffer from problems with generating enough friction between the device and the mucous-lined tract wall.

In this study we start to address the problem of generating friction in slippery environments by...
looking at nature for inspiration. One group of animals that successfully navigate in such environments is the ragworms of the polychaete family Nereididae. Throughout this study we focus on the common ragworm Nereis diversicolor, which is found in estuaries and shallow coastal waters in the Northern Temperate Zone[11]. It is found in habitats ranging from sandy mud and gravel to clay[12], where it can be found at a density of up to several thousand individuals per square meter[11].

What makes this species particularly useful from a biomimetic perspective is the diverse ways in which it can move through the medium. N. diversicolor is capable of burrowing through the substrate, crawling over the substrate and swimming in open water. During fast crawling and swimming the body undulates from side to side with each body wave moving from the posterior region to the anterior[13]. Lateral appendages—the parapodia—are synchronised with the body waves and aid in thrust generation by acting as paddles during swimming[14] and legs during crawling[15]. During slow crawling or, or only small amplitude, body waves are present and thrust is generated by the parapodia[15].

Protruding distally from each parapodium are three bundles of setae, which are the structures that allow the worm to crawl effectively in slippery substrates[16,17]. Each seta consists of a shaft and a serrated blade that are jointed and allow movement of the blade relative to the shaft in a limited number of directions[18]. This movement is entirely passive and presumably allows the seta to interact with the surroundings and maximise friction[18]. In this study we first looked at the morphological parameters of the parapodium-seta system and the dynamic parameters of the crawling worm. We then used the results obtained to design and test a robotic seta-like appendage, attached to a servomotor imitating the movement of the parapodia, against control appendages over a range of substrates. Our objective was to analyse why setae might be more advantageous than either no setae at all or simply larger parapodia.

2 Biological data

2.1 Materials and methods

Large juvenile Nereis diversicolor (length ~ 50 mm and weight ~150 mg) were used in this study. For the scanning electron microscopy (SEM), worms were obtained from SealBait Ltd. (Northumberland, UK), whereas the worm used in the dynamic analysis was collected in the Severn Estuary (South Gloucestershire, UK).

Specimens were prepared for the SEM by placing them in 2% glutaraldehyde for several days. The 15th segment and the 16th-18th segments were then dissected into two pieces. The dissected specimens were rinsed with a PBS-buffer and placed in 1% osmium tetroxide before being dried in a sequence of acetone; water sequence of increasing concentration. The specimens were then completely dried using a critical point drier and mounted. The single segment specimens were mounted to provide a frontal view of the parapodium. The three-segment specimens were mounted on the dorsal side so that a ventral view was possible. The specimens were then covered with a thin layer of gold by a sputter coater (Edwards S150B Gold Sputter Coater). Hereafter the specimens were ready for examination in the SEM (JEOL JSM6310).

The following data were extracted from the specimens. The digital images were analysed with ImageJ 1.29× (NIH, USA). Note that all measurements of seta-bundle and setal area come from the lower half of the parapodium, whereas the data on setal morphology come from setae in both the lower and upper halves of the parapodium.

• SEM – segment No. 15

Parapodial length: The distance from the base of the parapodium to the distal end.

Parapodial height: The distance from the trough behind the neuropodial cirrus to the trough behind the notopodial cirrus.

Parapodial area: The area of the entire parapodium including the setal bundles.

Bundle area: The area covered by the setae of the lower and upper neuropodial bundles.

Number of setae: The number of setae in the lower and upper neuropodial bundles.

Intersetal distance: The average distance
between neighbouring setae in a bundle. Calculated using the following equation:

\[ D = \frac{(W - N_d)}{(N - 1)} \]

where \( W \) is width of the bundle 100 µm distally from the base, \( N \) is the number of setae in the bundle and \( d \) is the average diameter of all setae, disregarding setal type, measured in this study (5.9 µm ± 0.9 µm). Note that the setae were not always placed in rows; sometimes the setal distance equation gave a negative value. In these cases the intersetal distance was set to zero.

Seta type: From the images of the joint region of individual seta it was possible to classify the setae into either heterogomph falcigers, heterogomph spinigers or homogomph spinigers.

Shaft length: The visible length of the setal shaft protruding from the parapodium.

Shaft diameter: The diameter of the setal shaft 15 µm below the setal joint.

Blade length: The length of the setal blade.

Blade diameter: The diameter of the setal blade 15 µm above the setal joint.

- SEM — segments Nos. 16—18

Parapodial width: The distance from the front to the end of the parapodium as seen from below.

Interparapodial distance: The distance between neighbouring parapodia. This measurement is an average of the distance from the 16th to the 17th segment and the distance from the 17th to the 18th segment.

To get information about the kinematics of crawling *N. diversicolor*, a worm was placed in a Petri dish filled with artificial seawater and, while crawling slowly, it was recorded with a digital high speed camera (The MotionScope 2000S, Redlake MASD, Inc.) at 125 frames/sec.

### 2.2 Results

SEM photos at low magnification revealed the overall shape of the parapodium (Fig. 1). The parapodia are asymmetrical with the upper part of the parapodium larger than the lower one and with many protruding parts (Fig. 1a), some of which are sensory organs[10]. Also conspicuous are the three protruding bundles of setae, one in the upper part and two close together in the lower (treated as a single bundle in the rest of this paper). A ventral view of the parapodium revealed that they are slightly tapering towards the distal end (Fig. 1b).

![Frontal view of one of the parapodia of the 15th segment](image1)

![Ventral view of segments 16th to 18th](image2)

Fig. 1 SEM photos of *Nereis diversicolor* (Numbered points and connecting lines define geometry of artificial parapodium (section 3.1))

Measurements on SEM photos of various magnifications were performed (Table 1). These showed that the parapodia are on average as long as they are high, with a width of 0.5 mm and spaced 0.2 mm apart. The lower seta-bundle covers almost 8% of the entire area of the parapodium and consists of 25 setae spaced 2 µm apart. Three different seta-types were found in the two seta-bundles: Heterogomph falcigers, which can be identified by having an asymmetrical collar around the joint between shaft and blade and a blunt ending of the blade; heterogomph spinigers, which also have an asymmetrical collar.
but have a tapering end of the blade; homogomph spinigers, which have a symmetrical collar and a tapering end of the blade. All three types had similar shaft diameters and lengths as well as similar blade diameters, but the blade lengths were different, shortest for heterogomph faligers and longest for homogomph spinigers (Table 1).

| Table 1 Morphological data from the parapodium and setae of *Nereis diversicolor* |
|---------------------------------------------|------------------|--------------|
| Sample size | Mean | Standard deviation |
| Parapodial length (mm) | 6 | 0.76 | 0.11 |
| Parapodial width (mm) | 6 | 0.54 | 0.1 |
| Parapodial height (mm) | 6 | 0.75 | 0.12 |
| Interparapodial distance (mm) | 6 | 0.18 | 0.1 |
| Parapodial area (mm²) | 6 | 0.64 | 0.18 |
| Bundle area (mm²) | 6 | 0.05 | 0.01 |
| Number of Setae | 6 | 25.2 | 2.3 |
| Interset distance (μm) | 6 | 1.9 | 1 |

| Heterogomph faliger |
|-------------------|------------------|--------------|
| Shaft length (μm) | 32 | 154.9 | 48 |
| Shaft diameter (μm) | 25 | 5.9 | 1.3 |
| Blade length (μm) | 32 | 33.4 | 7.4 |
| Blade diameter (μm) | 26 | 5.6 | 1 |

| Heterogomph spiniger |
|-------------------|------------------|--------------|
| Shaft length (μm) | 7 | 156.1 | 32.2 |
| Shaft diameter (μm) | 4 | 6.1 | 0.7 |
| Blade length (μm) | 27 | 141.6 | 17.3 |
| Blade diameter (μm) | 4 | 5.4 | 1 |

| Homogomph spiniger |
|-------------------|------------------|--------------|
| Shaft length (μm) | 48 | 139.3 | 58.1 |
| Shaft diameter (μm) | 56 | 5.9 | 0.8 |
| Blade length (μm) | 48 | 191.6 | 36 |
| Blade diameter (μm) | 56 | 5.3 | 0.6 |

3 Modeling parapodium and setae

3.1 Modeling biological shapes

The worm parapodium was replicated using a dimension rapid prototyping machine. The exact form of the parapodium was strictly not important for the experiments conducted but the replication was undertaken as an exercise in producing biological shapes. In common with many biological forms, the parapodium of *N. diversicolor* is extremely complex. In order to obtain an acceptable model of this appendage, it was necessary to simplify its geometry. A Pro/Engineer 2001® part was sketched starting from pictures captured through the SEM.

Eleven key points were marked out on the photo of the transverse section of a real worm (Fig. 1a). An interpolating spline was traced to get a similar cross-section border. The same method was used to generate a longitudinal profile (Fig. 1b). The achieved cross-section was extruded along the longitudinal profile. In this way, a three-dimensional shape was obtained with proportions very similar to the natural appendage of the real nereid. It is important to note, however, that the hydrostatic skeleton of the real worm allows its parapodia to change size and shape during the course of its motion²⁰. The worm, furthermore, has muscles that enable it to retract the parapodium during the recovery stroke and protract it again for the power stroke²¹. Neither of these effects could be captured by the simplified robotic model.

Fabricating an artificial parapodium was the objective of this modelling. Once built, the parapodium had to be inserted into an actuated mechanism, able to replicate the principal nereid locomotion gaits. Additional features were added to the natural geometry to make such an assembly technically feasible. These supplementary features did not interfere with the substrate, but facilitated interfacing to the servomotor. Fig. 2 shows the geometry of the artificial parapodium.

One set of parapodia was constructed without setae. A second set of parapodia was fitted with setae modelled using 0.4 mm diameter piano wire. Five lengths of piano wire were glued onto each parapodium to give a setal bundle area somewhat larger, in relative terms, than that of the lower setal bundles of the real worm. The relative setal area was increased so as to amplify any measured differences in the performance of the setal configurations. Unlike the real worm setae, the experimental setae were not jointed. A third set of parapodia was fitted with extension plates, where each plate covered the
Fig. 2 A CAD drawing showing the design of the artificial parapodium and its interface with the servomotor (front of parapodium visible)

full area of the sector of the circle over which the piano wire setae had been distributed when constructing the second parapodia set. This area was approximately 22% of the plain parapodium area. The three setal configurations are shown in Fig. 3.

3.2 Modeling polychaeta gaits

From observations of nereids moving in their natural environment, locomotion gaits were derived. During fast crawling and swimming, the parapodia move with the same frequency of oscillation as the body wave, timed so that power stroke of each parapodium is coincident with the crest of a passing body wave\cite{12}. The current work focused on the effectiveness of the parapodia without a body wave. The worm employs this type of locomotion gait during slow crawling. From video recordings of slow crawling worms we found that each parapodium had an angular stroke of approximately 90°, as shown in Fig. 4.

![Diagram of parapodium configurations](image-url)

(a) Plain parapodium  (b) Parapodium with 0.4 mm piano wire setae  (c) Parapodium with extension plate

Fig. 3 The three setae configurations tested (viewed from rear)

![Diagram of parapodium stroke angles](image-url)

(a) The beginning of the power stroke  (b) The middle of the power stroke  (c) The end of the power stroke

Fig. 4 Three snap-shot photos showing the parapodium position relative to the body during slow crawling in *Nereis diversicolor*
The sixth parapodium on the left was recorded in three positions: the extreme forward position, the intermediate position and then the extreme backward position.

By analysing the video recordings of crawling worms, a mean parapodial frequency of 1 – 1.25 Hz was observed. The rowing-like movement of a parapodium can be divided into two phases; during the first phase the appendage is pushing the nereid body forward (power stroke) and during the second phase the parapodium returns to its original position (recovery stroke)\(^\text{[15]}\).

We found the duration of the power stroke to be approximately twice that of the recovery stroke. An entire cycle of the rowing-like movement lasted approximately 0.8 s, with the power stroke lasting approximately 0.5 s and the recovery stroke approximately 0.3 s.

Two main strategies were observed: “step-like” and “row-like” locomotion. “Step-like” locomotion occurred during slow crawling. Successive parapodia oscillate with a phase difference of approximately 25°. The result is an apparent similarity with the walking of bipeds and quadrupeds, with the additional benefit of the body adjusting to the surrounding environment\(^\text{[22]}\). “Row-like” locomotion is instead a synchronised waging of parapodia, just like oars in a boat, and occurs during fast crawling and swimming in water\(^\text{[14]}\).

4 Robotic prototype

4.1 Fabrication of components

The robot frame and parapodia were designed using Pro/Engineer 2001\(^\text{®}\) and Solid Edge\(^\text{®}\) Version 14 CAD software and manufactured in ABS plastic on a dimension rapid prototyping machine. The robot frame was designed to accommodate a maximum of eight parapodia (four on each side of the frame), each driven directly by a GWS miniature servomotor. The dimensions of the worm parapodia were increased by a scale factor of 25 to give the dimensions of the robot parapodia. The inter-parapodal spacing with eight parapodia fitted was designed to the same scale and was equal to 18 mm and 47 mm in the axial and transverse directions respectively. Fig. 5 shows the robot fitted with four parapodia in the corner positions of the frame, giving an axial inter-parapodial spacing of 54 mm.

![Robot assembly](image)

**Fig. 5 Robot assembly**

4.2 Computer interface

The servomotors were controlled by a Pololu 16-servo controller connected to the USB interface of a personal computer. A Visual Basic\(^\text{®}\) interface (test-bench) was written to give maximum control over the locomotion parameters. The implemented gaits emulated the fluctuating movement of real parapodia. The parapodial movement is defined by posterior to anterior metachronal waves\(^\text{[15]}\). The parameters that characterise these waves are the frequency, the angular amplitude, the phase difference between neighbouring parapodia and the zero-position about which the parapodia rotate equally in either direction by an amount equal to the angular amplitude. The frequency defines the parapodial sweep speed, which was constrained by the Visual Basic\(^\text{®}\) software to be the same during the power and recovery strokes. Although the parameters that characterise the wave of a real worm parapodium are almost constant, the test-bench software was designed to be able to vary the parameters over a wide range of values, in order (in future work) to extract the best mix of variables able to determine the behaviour of an efficient and environment-adaptive robot.

The main window of the test-bench user interface is shown in Fig. 6. An additional control allows “step-like” or “row-like” locomotion to be introduced immediately with biomimetic parameters.
These parameters were determined in Section 3.2 and consist of frequency equal to 1 Hz, amplitude equal to 45° (overall stroke equal to 90°) and zero-position equal to $-15°$ (i.e., each parapodium swings about a central position shifted towards the robot’s rear by 15° with respect to the normal to the body’s axis). The associated phase-delays are 25° and 0° respectively. Controls allow each of the parameters to be adjusted independently and, in addition, the starting position of one of the front parapodia can be specified, with the other parapodial starting positions then defined by the specified phase difference. After the motion is stopped, the parapodia can be made to return to either their zero positions or their starting positions. Servo offsets can be slightly adjusted in order to correct small assembly errors and eight dynamic scroll-bars visualise the expected movement of the artificial parapodia in real time.

![Testbench Control For Polychaeta-like Artificial Parapodias](image)

**Fig. 6** The main window of the test-bench user interface

### 4.3 Measurement system

The horizontal thrust of the robot was measured using a piezoresistive force sensor with a maximum range of 0 to 500 g (Honeywell part No. FSL05N2C). The robot was tethered to the end of an arm pivoted about a vertical axis, which also rested in contact with the force sensor (Fig. 7). This arrangement gave a variable gain mechanical amplifier, the gain of which was set by choosing the distance of the force sensor from the pivot of the arm. Since the force sensor operates only in compression and the robot generated thrust in both the forward and backward directions, it was necessary to preload the force sensor by attaching the front of the robot to a vertically suspended weight via a thread running over a pulley. Unlike the worm, the robot generated thrust in both directions because the robot parapodia did not lift away from the substrate during
The force sensor contains a Wheatstone bridge circuit and was connected to a differential amplifier, the gain of which was adjusted to give a 0 to 10 V output over the required thrust range. A data acquisition unit (Measurement Computing part No. PMD1209FS) recorded the amplifier output voltage over a period of 10 s at a sampling rate of 1000 samples per second, using LabVIEW® software. A set of weights was used to calibrate the force sensor before and after conducting the experiments. Both linearity and repeatability were found to be good and a mean sensitivity of 42 mV/g was used to convert acquired voltages to thrust in grams.

5 Experiments

5.1 Materials and methods

In all experiments, the robot was configured with four parapodia (two on each side of the frame, as shown in Fig. 5) operating in phase (i.e., “row-like” locomotion) at a frequency of approximately 1 Hz. Relative to the parapodial dimensions, the interparapodial spacing was therefore larger than that of the worm, since four rather than eight parapodia were fitted. The angular amplitude of the parapodial motion was 25° either side of a zero position 15° rearward of the normal to the side of the robot body.

The angular amplitude was smaller than that of the real worm parapodia (Section 3.2). This was to allow comparison with future experiments with eight parapodia fitted to the robot frame, under which conditions the angular amplitude is limited to 25° by mechanical interference between neighbouring parapodia. The power and recovery strokes were of equal duration as stated in Section 4.2. Prior to an experiment, each parapodium was moved to the position of the start of the power stroke, i.e., 10° forward of the normal to the side of the robot body. To perform an experiment, the robot was then lowered gently onto the required substrate using a vertical suspension thread to minimize the introduction of horizontal frictional forces between the robot and the substrate. These frictional forces had the effect of changing the measured pre-load on the robot imposed by the attached vertically suspended weight. Data acquisition was then started and, after an interval of approximately 1 s, the robot motion initiated. The robot was stopped after 8 s and the data acquisition terminated approximately 1 s thereafter. In this way, data was captured for around seven full cycles of the robot parapodia. Acquiring some data immediately before and after initiating the robot motion allowed the values of the static pre-load on the force sensor to be observed. Each experiment was repeated twenty times under identical condition.

The two experimental variables investigated were substrate particle diameter and setal configuration. The three substrates used were fine sand with a mean particle diameter of 0.5 mm±0.2 mm (sample size equal to 84, measured from SEM photos), coarse sand with a mean particle diameter of 1.4 mm±0.2 mm (sample size equal to 34, measured from SEM photos) and gravel with a mean particle diameter of 6.2 mm±1.6 mm (sample size equal to 158, measured from digital photos). The three setal configurations consisted of plain parapodium with no setae, parapodium with piano wire setae and parapodium with extension plate, as described in Section 3.1.

Data analysis concentrated on the first power stroke of the robot motion for two reasons. Firstly, the depth of parapodial penetration into the substrate could not be guaranteed to be consistent between repeated experiments at the start of any power stroke other than the first, since the robot rapidly sank into the substrate during its motion. This sinking was a result of the absence of a robot body in contact with the substrate and was thus unrepresentative of the
worm’s behaviour. Secondly, since the robot did not lift its parapodia during the recovery stroke and the inter-parapodal spacing was not to scale and the durations of the power and recovery strokes were equal, the state of the substrate might not have been representative of that encountered by the worm except during the first power stroke of the robot motion. Concentrating on the first power stroke also meant that the shape of the front surface of the parapodium was not critical.

A data analysis program was written in FORTRAN 77 to extract from the acquired data the peak value of thrust during the first power stroke of each experiment and record the time relative to the start of the stroke at which this peak occurred. The mean peak thrust was then calculated for each set of twenty experiments performed under identical conditions. The mean peak thrust was then plotted as a function of substrate particle diameter for each of the three setal configurations.

The thrusts generated for all parapodal configurations and substrates were analysed using a two-way ANOVA with the substrate particle size and parapodal configuration as fixed factors. Data was logarithmically transformed to achieve normality, but equal variances were not achieved. The Tamhane’s T2 test, which assumes unequal variances, was therefore employed for post hoc comparisons. Similarly statistics were used to compare the time from the beginning of the power stroke until the maximum thrust was reached. Here, substrate and parapodal configuration served as fixed factors. For all tests a significance level of $\alpha = 0.01$ was chosen. Tests were performed with SPSS 12.0 for Windows (SPSS Inc., 2003).

5.2 Results

All three parapodal configurations showed a general trend of an increase in thrust with an increase in particle size (Fig. 8). Here, the peak thrust during the first power stroke of the parapodal motion has been plotted; similar trends are observed if the mean thrust over the power stroke is plotted instead. Statistically significant effects of both particle size (Two-way ANOVA: $F_{(2,10)} = 145.4, P < 0.01$) and parapodal configuration (Two-way ANOVA: $F_{(2,10)} = 147.1, P < 0.01$) were found. A significant effect of the interaction between those was also observed (Two-way ANOVA: $F_{(6,10)} = 18.8, P = 0.01$). From Fig. 8 it can be seen that the setal configuration showed a steeper increase in thrust with increasing particle size than both the plain and plate configurations. The setal configuration outperformed the plate configuration at the largest particle size. The post hoc Tamhane’s T2 test revealed that the plate and setal configurations outperformed the plain configuration across all particle sizes. It also showed that significantly higher thrust was generated in the gravel substrate compared to the two other substrates.

![Maximum thrust generated](image)

**Fig. 8** The maximum thrust generated by the worm robot over one power stroke for each parapodium configuration and as a function of substrate particle size. The sample size for each point is $n=20$. The 3 particle sizes were 0.5 mm (fine sand), 1.4 mm (coarse sand) and 6.2 mm (gravel). The error bars indicate the standard deviation.

A closer examination of the behaviour of the thrust generated in the three substrates revealed that the maximum thrust generally was generated 200 - 300 ms into the power stroke (Fig. 9). However, the same pattern was observed for all substrates, with the plain configuration reaching the maximum faster than the setal configuration and the plate configuration reaching its maximum later than the other two. A statistical test confirmed that the effect of parapodium configuration was significant (Two-way ANOVA: $F_{(2,10)} = 13.6, P < 0.01$), whereas neither the effect of substrate (Two-way ANOVA: $F_{(2,10)} = 4.6, P = 0.01$) nor the interaction between the two effects (Two-way ANOVA: $F_{(4,10)} = 2.4, P$
compared with the setal diameter, it is suggested that the setae simply slide between the substrate particles thus generating little thrust. In the limit of infinitesimal substrate particle diameter, setae might be expected to offer no benefit at all, which Fig. 8 appears to suggest. Under these conditions, larger parapodia would still be expected to offer a benefit, which is also suggested by Fig. 8. When the substrate particle diameter is large compared with the setal diameter, the setae are unlikely to slide between substrate particles, but instead the setae will generate thrust as a result of the resistance of the substrate particles. It is unclear exactly why the thrust should be larger with setae than with parapodia enlarged to cover the setal area but it is likely that the setae are better able to conform to the substrate particle shape. Particles with diameters larger than the spacing between the setae can be trapped between these and thus not roll out of the way of the moving setal configuration as easily as with the moving plate configuration. It is known from both theoretical analyses\(^\text{[23,24]}\) and experiments\(^\text{[25]}\) that the spacing of hair-like cylinders is important for their function in aquatic environments.

Hair-like structures similar to the setal bundles found in nereids have been found to work either as sieves or as plates depending on the spacing and Reynolds number at which they operate in a range of organisms, including copepod suspension feeding\(^\text{[26]}\), sniffing in silk moths\(^\text{[27]}\) and swimming in mosquito larvae\(^\text{[28]}\). It is possible that the spacing of hair-like structures plays an equally important role in a slippery substrate consisting of small particles. Further experiments with varying the setal spacing/particle size ratio are needed to determine this. The real compound seta found in errant polychaetes consists of two parts, a blade that can move independently of a shaft, and this probably allows the setae to conform to the substrate in a way that the stiff one-part setae used in the experiments presented here cannot\(^\text{[18]}\). Experiments conducted by Merz and Edwards\(^\text{(1998)}\)^{[17]} show that worms with both the setal blade and the joint ablated crawl slower than worms with only the blade ablated. Experiments that com-

![Graph showing time until maximum thrust for different substrate types](image)

**Fig. 9** The time from the beginning of the power stroke until the maximum thrust is generated for each parapodial configuration and substrate. Each column represents the mean of 20 samples and the error bars indicate the standard deviation.

6 Discussion

Thrust is generated by the appendages pushing against the substrate, both in our robotworm and in the real nereid worm\(^\text{[15,16]}\). It was therefore expected that adding area to the appendage would give increased thrust. This was confirmed by our study showing a significantly lower thrust production in plain parapodia as compared to when an attachment was added (Fig. 8). However, more surprising was that the results of the preliminary experiments described in Section 5 suggest that, as the substrate particle diameter is increased, a point is reached where the robotworm generates more thrust by having setae attached to its parapodia than would be the case were the parapodia simply enlarged to cover the setae area. Dimensional analysis can be used to predict the substrate particle diameter at this crossover point for the worm, based on the experimental data. The crossover particle diameter can then be compared to the particle diameters of the substrates in which the worm operates to see what benefit the setae may have.

When the substrate particle diameter is small
pare two-part artificial setae with rigid setae are needed to determine whether higher conformity to the substrate would result in higher thrust generation in our robot.

The above discussion suggests that the relevant dimensionless group should be the ratio of the substrate particle diameter \((d_{\text{ms}})\) to the setal diameter \((d_{\text{s}})\). Table 2 shows values of this parameter for the experimental and worm environments. *N. diversicolor* can be found in a range of substrates\(^{(1)}\); here only two particle diameters, mud and fine sand, are included. Considering these results together with those of Fig. 8 implies that setae will contribute differently to the thrust when the worm is operating in mud, since this is approximately equivalent to fine sand in the experimental environment, compared to when the worm is operating in fine sand. The crossover point in Fig. 8 occurs at a substrate diameter of approximately 3.4 mm in the experimental environment, which corresponds to a diameter of approximately 50 \(\mu\)m in the worm environment. This diameter is an order of magnitude larger than the mud particle diameter and an order of magnitude smaller than the fine sand particle diameter. However, some caution is necessary when transferring the result found here for robotic locomotion on a dry substrate to the marine environment of the real worms. Muddy cohesive sediments are known to behave like an elastic solid\(^{(2)}\), and this will probably change the quantitative findings presented in this study although most likely not the qualitative ones. Further data from thrust generation on wetted substrates, and not least from studies on the locomotory behaviour of real worms in various substrates, are needed to determine the precise functional relationship between seta diameter and substrate particle diameter in errant polychaetes.

The difference between the stiffness of the worm setae and the artificial setae can be determined by calculating the bending stiffness in each case. The bending stiffness \(k\), is defined by the following equations:

\[
k = \frac{E I}{L^3}
\]

\[
I = \pi \left( d_s^4 - d_i^4 \right) / 64
\]

where \(E\) is the Young’s Modulus of the material and \(I\) is the second moment of area about its axis of a hollow circular shaft with inner and outer diameters \(d_i\) and \(d_s\) respectively. The displacement \(y\) of the setal tip under a point force \(F\) applied at the tip is then given by the following equation:

\[
y = \frac{FL^2}{3k}
\]

where \(L\) is the setal length. This equation can be recast in the following form:

\[
y / F = 1 / k'
\]

where \(1 / k' = L^2 / (3k)\) is a measure of the displacement per unit force such that \(k'\) is a measure of the effective bending stiffness. Assuming that a seta is made up of one third chitin and two thirds protein\(^{(3)}\) with Young’s Moduli of 150 GPa and 10 GPa respectively\(^{(4,5)}\), then the Young’s Modulus of the seta can be estimated to be 50 GPa from a simple rule of mixtures. Gustus and Cloney (1973)\(^{(6)}\) studied setae of 1 \(\mu\)m inner diameter and 2 \(\mu\)m outer diameter. Taking the outer diameter of the *N. diversicolor* seta to be 6 \(\mu\)m (Table 1) and assuming the same inner-to-out diameter ratio gives a \(k'\) of 0.33 N/m for a setal length of ~300 \(\mu\)m (Table 1). Assuming a Young’s modulus of 200 GPa for the artificial setae constructed from 0.4 mm diameter solid steel piano wire with length ~10 mm gives a \(k'\) for the artificial seta of 750 N/m. The experimental se-

### Table 2 The ratio of substrate particle diameter to setal diameter on various substrates for both the worm robot and the real worm

<table>
<thead>
<tr>
<th>Environment</th>
<th>(d_{\text{ms}}) (mm(^3))</th>
<th>(d_{\text{s}}) (mm(^2))</th>
<th>(d_{\text{ms}}/d_{\text{s}})</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Experimental environments</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fine sand</td>
<td>0.5</td>
<td>0.4</td>
<td>1.3</td>
</tr>
<tr>
<td>Coarse sand</td>
<td>1.4</td>
<td>0.4</td>
<td>3.5</td>
</tr>
<tr>
<td>Gravel</td>
<td>6.2</td>
<td>0.4</td>
<td>16</td>
</tr>
<tr>
<td><strong>Worm environments</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mud(^{(1)})</td>
<td>0.005</td>
<td>0.006</td>
<td>0.83</td>
</tr>
<tr>
<td>Fine sand</td>
<td>0.5</td>
<td>0.006</td>
<td>83</td>
</tr>
</tbody>
</table>

\(^{(1)}\) The diameter of the substrate particles.

\(^{(2)}\) The diameter of the seta. For the real worms it represents an average value for the shaft diameter of all setal types combined.

\(^{(3)}\) The measure of mud particle diameter comes from a sample of clay-like mud collected from the Severn Estuary (South Gloucestershire, UK). Measurements were made from SEM photos.
tae were therefore very much stiffer than the worm setae and were thus less able to conform to the substrate. However, they were still useful for a first understanding of the role of setae in thrust generation.

Fig. 9 shows that the time into the power stroke at which the maximum thrust occurred did not show substrate dependence but that there was a consistent variation with setae configuration. The maximum thrust was reached earliest when there were no setae, slightly later with setae and slightly later still with plates. A time of 250 ms into the power stroke corresponded approximately to the parapodial mid-position, i.e. 15° back from the normal to the side of the robot frame. It is interesting to note that the maximum thrust did not occur when the parapodium passed through the normal to the side of the robot frame, as might be expected since the thrust vector would then be pointing directly rearwards. No data on thrust generation is available from the real worm, however. The observations relating to the time at which the maximum thrusts occurred are currently not fully understood.

The power input to the robot was not measured during the experiments so it is not possible to compare the efficiencies of the three setal configurations. Efficiency calculations would, however, not be trivial since the size and weight penalties associated with the different setal configurations would also have to be considered. The objective of the experiments was simply to determine if setae offered any advantages over larger parapodia in terms of thrust generation, and the results of this study suggest that such advantages can be found for relatively large particle substrates.

7 Conclusion

This paper addresses the problem of generating friction in slippery substrates by taking inspiration from ragworms. Polychaetes can be found in a great variety of environments, which range from the depths of the ocean (swimming) to the sand of the seashore (crawling). Their versatile structure is a direct consequence of their adaptation to such diverse habitats and therefore they can be exploited as a model for a new generation of self-adaptive walking robots.

In particular, large juvenile *N. diversicolor* were studied with SEM and a digital high-speed camera, with the purpose of extracting morphological and kinematics data from the specimens. Scaled worm parapodia were replicated using a rapid prototyping machine and a robotic model was fabricated, after the necessary simplification of the complicated appendage geometry and of their complex biomechanics. Three sets of parapodia were constructed (without setae, with five stiff setae and fitted with extension plates) to determine if setae offered higher thrust over larger appendages. A computer interface able to control the main key parameters (frequency, amplitude, phase-delay and zero-position) was written and a measurement system using a pre-loaded force sensor and a data acquisition unit was conceived and set-up.

Experiments, which were performed on three different substrates (fine and coarse sand and gravel) and with the above three parapodial configurations, showed that the thrust increases with particle size. Furthermore, with sufficiently coarse gravel, the robot generates more thrust with setae attached to its parapodia than with parapodia enlarged to cover the setae area. This suggests larger parapodia offer most benefits when particle diameter is small compared with setae size.

The results obtained in this study indicate that robots required to move in a slippery substrate, consisting of small particles, could enhance their thrust production by employing small hair-like structures at the ends of the propulsive appendages. Thus such structures should be considered in self-moving endoscopes or robots needed to inspect sewage pipes or explore sandy areas. Although setae are better than a simple extension of the propulsive appendage only at relative large particle diameters, they confer an advantage over large appendages in that they can more easily be retracted or folded away when not in use, such as during the recovery stroke or locomotion in less slippery terrain.
Future work will comprise experiments varying the setal spacing/particle-size ratio in order to determine the exact role of hair-like structure spacing in slippery substrates. In addition, the fabrication of new artificial setae that are more biomimetic is required. In fact, a real biological seta consists of two parts, a shaft and a blade elastically connected to each other, unlike the artificial setae considered in this paper. Such a jointed structure allows biological setae to conform better to the surrounding environment. Furthermore, worm setae are much less stiff than the artificial ones which we used. Finally, experiments with an eight-parapodia-robot will be performed and a deeper study of the single setal shape will be made. The fact that unexpected benefits were found even for such crude artificial setae as were used in this study provides considerable justification for more detailed work in this area.

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