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Robustness of centipede-inspired millirobot locomotion to leg failures

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Abstract— **This paper explores the use of mechanical redundancy to enhance robustness to leg failures in miniature ambulatory robots. Graceful degradation, rather than immediate catastrophic failure, is exhibited experimentally in 10-20 leg centipede-inspired millirobots as legs are removed without altering the gait, using speed and radius of curvature as performance metrics. Static stability retention is examined as a function of the nominal number of legs, and for cases where static stability is lost, two gait options are tested. The effect of location of missing legs on performance is also described.**

I. INTRODUCTION

In nature, it is common for legged arthropods to experience limb failure. A study on Harvestmen collected in nature found that nearly half of the samples had at least one leg missing with twenty-five percent having two or more legs missing [1]. A similar study on the Spider *Scytodes globula* showed that out of 162 field collected samples, 36 had missing legs, with a higher percentage having the front legs missing than any other legs [2]. An extensive study of 2560 centipedes showed approximately 33 percent with one of the last legs missing and 25 percent with any other leg missing [3]. While many small creatures have the ability to regenerate limbs, it sometimes takes weeks for this to occur [4], requiring the creature to be able to locomote to feed or escape predators in the meantime. A study on Wolf Spiders showed that in the presence of leg failures, the average speed of locomotion decreased from 15 cm/s to 11 cm/s for males and approximately 25 cm/s to 18 cm/s in females [5]. Similar results have been found in Harvestmen [6]. Additionally, to maintain static stability, particularly at lower speeds, many creatures will alter the phase between legs to account for missing legs [7].

Robustness strategies focusing on sensing the location of missing limbs and altering the gait to maintain static stability have been formulated for legged robots both in simulation [8], [9], [10], [11], [12], [13], [14], [15] and experiments [16], [17]. The strategies used for these macro-scale robots focus on adapting gaits to maintain static stability and forward locomotion rather than on designing redundancy into the system. At larger scales, it is feasible to introduce sensors to specify the location of missing legs and compute new gaits. The robot used in [17] to compute fault tolerant gaits has 19 DOF, 60 sensors, and 8 computers. However, as robots are scaled down, computing power is limited, sensors become more costly due to smaller payload capacity, and robots tend to be underactuated. While different gaits have been studied in simulation for macro-scale robots with 4, 6, and 8 legs, an experimental study looking at performance degradation as a function of nominal number of legs has not been performed.

To fulfill the demand for small, agile robots for swarm robotics applications, multiple miniature legged robots have been created. Most of these weigh on the order of 20-30 grams [18], [19] or 1.5-2.5 grams [20], [21] and are modeled after rigid body hexapods. Similar to their biological counterparts, it is expected that these robots will suffer limb failures when in use. Many of the robots at this scale are underactuated, using one motor or drive signal for leg pattern generation and another to introduce asymmetries for turning. This makes it mechanically difficult, if not impossible, to alter the gait to account for specific missing legs even if there is enough payload capacity for controllers and sensors to compute new gaits. Given this limitation, we hypothesize that a robot with more mechanical redundancy, such as a myriapod-like body morphology, will allow legs to be lost while maintaining static stability and forward locomotion capabilities without altering the gait.

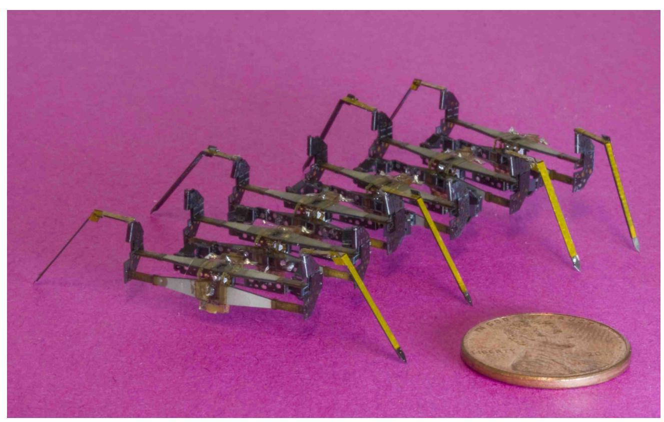

Fig. 1. Centipede millirobot with multiple missing legs adjacent to a U.S. penny for scale.

To understand the benefits of having many legs as it relates to locomotion robustness when leg failures occur, the following questions need to be answered:

1) How many legs can be lost before an underactuated n-segment millirobot is no longer statically stable without changing the gait to account for missing legs?
2) What is the decrease in performance as a function of percentage of missing legs and does robustness to leg failures increase with nominal number of legs?
3) Is there any benefit to having sensors on-board to identify missing legs and adjust the gait to maintain static stability or improve forward locomotion?

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4) Does the location of missing legs affect performance?

To answer these questions, the static stability as a function of number of legs, number of missing legs, and phase between segments was evaluated (Sec. III). Sec. IV describes the experimental approach taken to understand practical limitations of robustness using the centipede-inspired millirobot presented in [22] with 3, 5, 6, 7, and 10 segments. This work shows that even with significant leg losses, the centipede millirobot displays performance degradation, instead of catastrophic failure, even without altering the gait (Sec. VI). Sec. VII discusses which gait to choose when too many legs are missing and static stability is compromised. Sec. VIII shows that the location of missing legs along the length of the body does not affect performance and that there are larger decreases in speed when more legs in a row are missing due to off-axis body compliance.

II. NOTIONAL DESIGN AND FABRICATION

The millirobots used in this study (Fig. 1) are similar to those in [22] and are created using the PC-MEMS process [23]. Each segment has two actuated degrees of freedom, swing and stance, controlled by piezoelectric actuators with orthogonal four-bar transmissions. The actuators are coupled across the body such that when one leg is lifted, the opposite leg is placed on the ground. The passive backbone consists of linear and torsional springs. Improvements in this version include adding castellated joints to the backbone to reduce unwanted off-axis compliance. The dimensions for one segment are 4 by 1 by 1.2 cm, weighing 220 mg.

III. STATIC STABILITY

It has been found that for an underactuated centipede millirobot with n segments, a passive backbone, and no missing legs, the best gait, in terms of speed and cost of transport, typically has a phase between adjacent segments of $\frac{360}{n-1}$ degrees [22]. To avoid body supported locomotion, it is desirable to maintain static stability. Concerning static stability of a millirobot with missing or broken legs, there are three cases to consider:

1) No legs are missing.
2) A few legs are missing, but not enough to compromise static stability (i.e. the groups of stance legs form at least a tripod along the length of the body).
3) Too many legs in a row or legs on the first and last segment are missing, and static stability is compromised.

For the first and second cases, the gait does not need to be altered from the optimal undulatory gait to maintain static stability; however, for the third case, the gait has to be altered.

Using the optimal undulatory gait, the number of segments in a row that can be missing legs before the millirobot loses static stability is $n_{critical} = floor(0.5(n-3))$. This arises from the fact that, using a constant phase between segments and having contralaterally coupled legs, the maximum phase between two adjacent fully functional segments cannot be greater than 180 degrees. As the number of segments increases, the number of segments in a row that can be broken asymptotes to 50 percent of the total number of segments. In terms of static stability for underactuated robots, this suggests the benefit for having more legs is more apparent when comparing 3-segment robots to 5-segment robots as opposed to comparing, for example, a 20-segment robot to a 21-segment robot (Fig. 2).

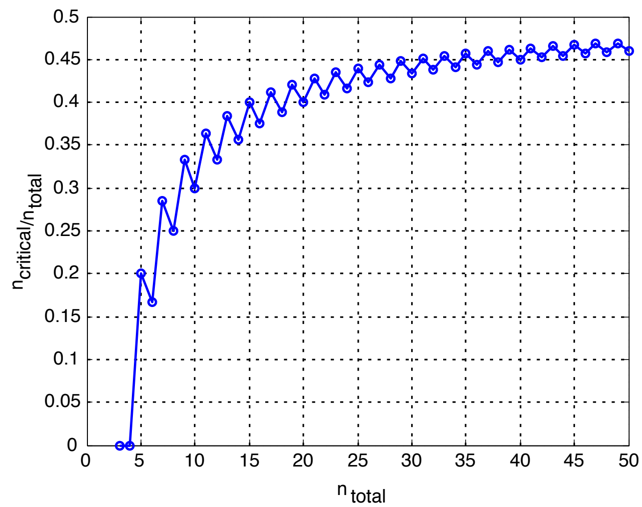

Fig. 2. Maximum percentage of segments in a row that can be missing before an n-segment millirobot loses static stability.

While $n_{critical}$ is merely dependent on the nominal number of segments, the total number of legs that can be missing depends on the location of the missing legs. For example, if the first, middle, and last segments are fully functional, all additional legs can be lost and the millirobot will still maintain static stability without altering the gait from the nominal undulatory gait.

For the optimal undulatory gait, the first and last segments cannot be broken without compromising static stability. Using a phase slightly larger than the optimal undulatory gait, such as $\frac{360}{n-2}$ degrees, would allow the first or last segment to be lost without having to alter the gait and with little performance difference compared to the optimal undulatory gait for a millirobot with no missing legs, particularly for millirobots with many legs. However, the tradeoff is that less segments in a row could be missing before static stability is lost. This strategy could be useful if it is expected that anterior or posterior legs are more likely to become damaged than middle legs as occurs in many arthropods [2], [3].

IV. EXPERIMENTAL METHODS

An experimental approach was taken to investigate performance degradation as a function of number and location of missing legs. Millirobots with 3, 5, 6, 7, and 10 segments were tested open-loop over a range of frequencies (1-15 Hz) using an external power supply and controller on flat terrain. Each data point in Figs. 4-6 is the average of two trials for a unique combination of missing legs. Trials were chosen to obtain combinations of missing legs to answer specific questions. 31 cases with different numbers of legs in a row missing, legs missing at different locations along the length of the body, and varying total numbers of legs missing for each millirobot size were tested with two drive signals for each case. Examples of test cases can be found in the Supplementary Video.

Legs were disabled by disconnecting the segment drive signal and completely removing them from the hip joint, eliminating interference of the leg with adjacent segments or terrain. The extent to which this accurately represents real situations is unknown as there could be multiple modes of failure, including actuator failure, leg removal, or transmission damage. While leg interference with adjacent segments could be detrimental to locomotion, the problem of body sagging described in Sec. VIII may be alleviated if legs remain attached and assist with supporting the weight of the damaged segment due to the inherent hip joint stiffness. Compared to the segment mass, leg masses are negligible, therefore lost legs do not affect the weight of the millirobot.

V. BASELINE SPEEDS

The performance metric for robustness to leg failures was chosen to be the percent decrease in speed, v_d, relative to the baseline speed, v_b,

$$v_d = \frac{(v_b - v_m)}{v_b} \times 100 \tag{1}$$

where v_m is the speed when legs are missing. v_d was chosen in place of absolute speed since millirobots of different lengths exhibit different baseline speeds. Baseline speeds were collected for each millirobot length using the optimal undulatory gait (Fig. 3). The speeds for most of the millirobots, particularly those with 6, 7, and 10 segments, are not linear with driving frequency, but rather have a slower rate of increase at frequencies higher than 10 hz. This is due to a combination of the dynamics of body undulations, foot/ground contacts, and limited ramp rate of the trapezoidal drive signal.

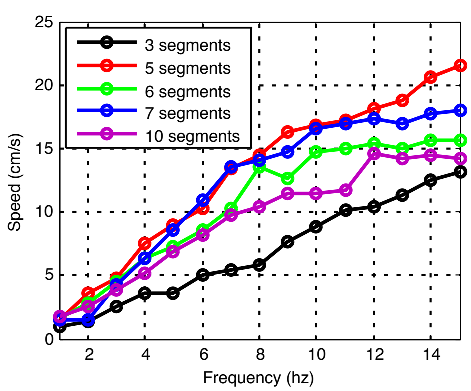

Fig. 3. Baseline speeds for millirobots with 3, 5, 6, 7, and 10 segments with no missing legs.

VI. PERFORMANCE DEGRADATION

In order to determine if having more nominal legs results in a lower v_d without altering the gait, the decrease in speed as a function of the percentage of missing legs is plotted in Fig. 4 for various frequencies. It is important to note that for all of the points for 5, 6, 7, and 10 segments, static stability was not compromised by the removal of legs; however, for the data points for 3 segments, static stability was always lost as no legs can be removed from a 3-segment millirobot with contralaterally coupled legs without compromising static stability.

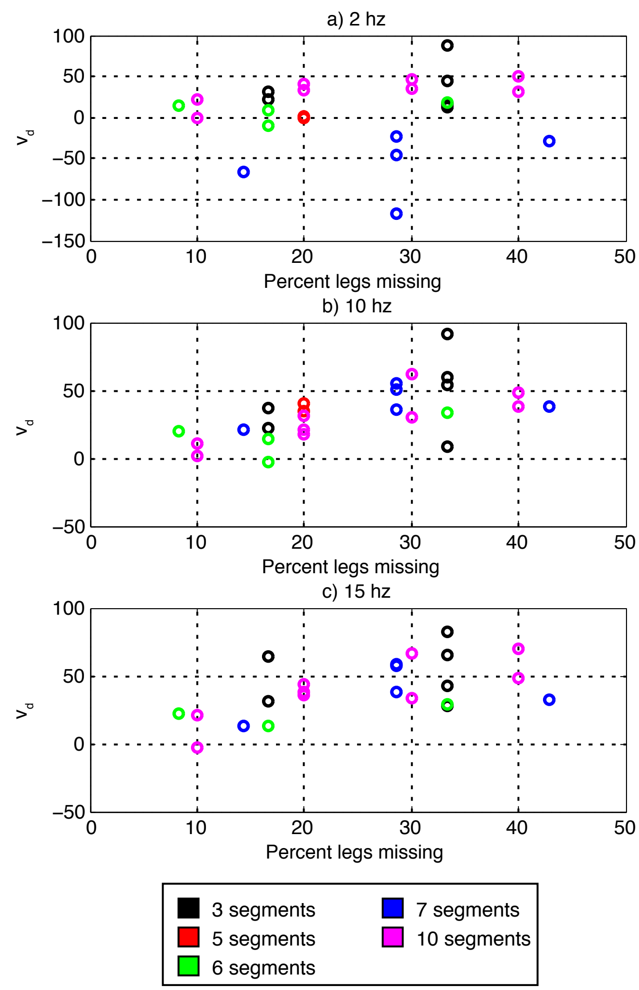

Fig. 4. Percent decrease in speed as a function of the percentage of missing legs for various frequencies.

For cases in which the gait is not altered, the experimental results show that, as expected, there is an upward trend in v_d as a function of the percentage of missing legs (Fig. 4). While the decrease in speed does become more severe with the percentage of missing legs, Fig. 4 shows that missing legs do not render this millirobot incapable of locomotion even when the gait is not altered. For example, one case shows that a millirobot with 7 segments can have 43 percent of legs missing and only experience a 40 percent decrease in speed if the location of missing legs does not affect static stability. Additionally, for a 10-segment robot, 40 percent of legs can be missing and the decease in speed ranges from 48 to 70 percent without altering the gait. Note that for these cases, the broken segments were not all adjacent as that would result in a loss of static stability. There is variation among the data depending on the number of missing legs in a row, which is discussed further in Sec. VIII.

Fig. 4(b-c) shows that v_d for hexapods is at the higher end of the range for the millirobots tested, although the decrease in speed is not significantly higher than that of millirobots with nominally more legs. Conversely, v_d as a function of absolute number of missing legs (Fig. 5) shows that having more than 5 segments results in less of a decrease in speed as legs are lost. For example, when 1-2 legs are missing, only having 3-5 segments results in speed decreases between 25-95 percent, while for 6, 7, and 10 segments, having 1-2 broken legs only causes a decrease in speed of 0-25 percent. If the number of expected leg failures is linear with the total number of legs, Fig. 4 suggests that, aside from a few critical cases, there may not be a benefit in terms of robustness to having more legs. Alternatively, if the expected number of leg failures is a sublinear function of the total number of legs, Fig. 5 suggests that there could be a performance advantage to having at least 6 segments. There is minimal difference in v_d between 6, 7, and 10 segments.

As discussed in Sec. III, the number of legs that can be lost without compromising static stability increases with the number of segments. For all data points in Fig. 4 and Fig. 5 associated with millirobots with more than 3 segments, static stability was maintained without altering the gait. Every trial for the 3 segment millirobot resulted in a loss of static stability due to the contralateral leg coupling, which cannot be fixed even by altering the gait. In many cases, this causes body-supported locomotion. There are also some cases for hexapods that cause critical failure. For example, if the middle legs are missing and the gait is not altered, the remaining segments are in phase, causing the robot to locomote laterally.

The decrease in performance is also frequency dependent, with less of a decrease occurring at lower frequencies, such as 1-4 hz. In some cases, particularly for 7 segments, the speed can increase when legs are missing. This is shown as a negative v_d in Fig. 4(a) and is a result of the natural dynamics of the segments, which are altered when legs are missing (i.e. robot mass stays constant but hip stiffness is eliminated for missing legs). While the speed for a fully functional millirobot levels out slightly above 10 hz, the average speed for millirobots with multiple missing legs begins to level out at 5 hz (example cases shown in Fig. 9 and Fig. 10). This results in a larger decrease in speed at higher frequencies and a lower maximum achievable speed.

An additional performance metric that gives an indication of the stability of the system is the radius of curvature of the path of the center of mass (COM), R_c. For desired straight-line locomotion, if R_c decreases significantly as segments are removed, the direction of the millirobot may be more difficult to control. Fig. 6 shows that while there is not a significant correlation between R_c and the percentage of missing legs, R_c for 3 segments with missing legs is generally smaller than that with more segments when legs are removed for

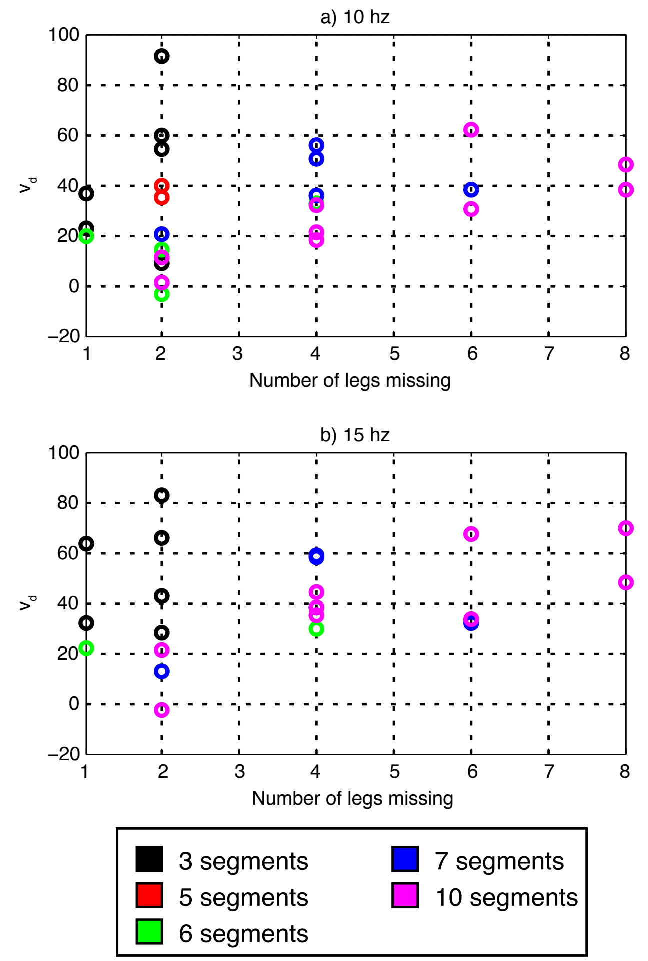

Fig. 5. Percent decrease in speed as a function of the number of missing legs for various frequencies.

cases in which the gait was not altered. This is likely due to the loss of static stability. With all legs intact, the 3-segment millirobot demonstrated R_c of similar magnitude to the other millirobots tested, showing that having more than 3 segments may help in preserving the directionality of the straight-line gait.

VII. BENEFITS TO CHANGING GAIT

A. Static stability conserved

If less than $n_{critical}$ segments in a row are broken and the first and last segments remain fully functional, static stability is not compromised, and it is not necessary to alter the nominal straight-line gait. However, if v_d is significantly less when altering the gait, it could be beneficial to have additional controllers and proprioceptive sensors on legs. Two different strategies were compared for a variety of combinations of missing legs:

1) Unaltered gait: The gait is not changed from the nominal gait (optimal undulatory gait) with a constant phase of $\frac{360}{n-1}$ degrees between all segments.
2) Nonexistent gait: The gait is changed and a constant phase of $\frac{360}{n-(n_m+1)}$ degrees between fully functional

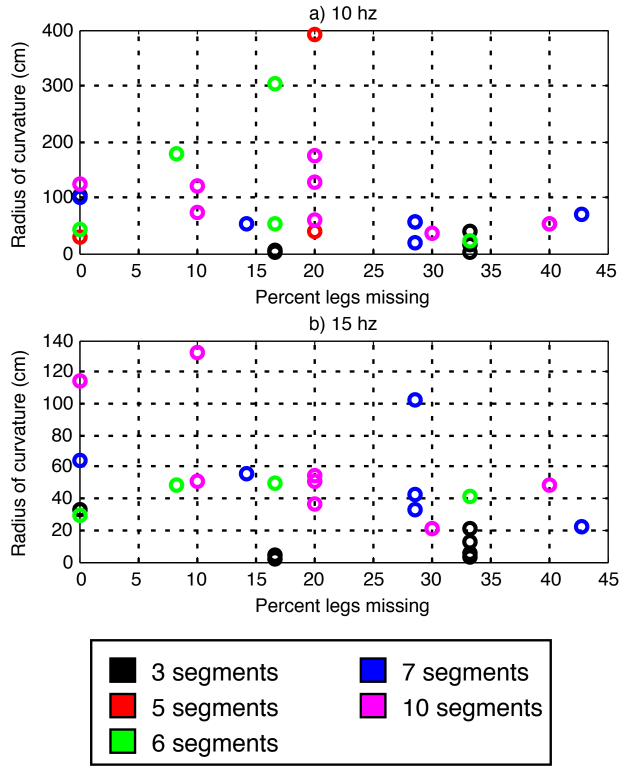

Fig. 6. Radius of curvature as a function of percent of segments with missing legs for various frequencies.

segments is used, where n_m is the number of broken segments.

Both of these strategies are illustrated in Fig. 7(a). The unaltered gait does not require proprioceptive sensing, whereas the nonexistent gait uses knowledge of which segments are broken and alters the gait to act as if those segments do not exist. For example, with the nonexistent gait, a 6-segment millirobot with one broken segment would use the optimal undulatory gait for a 5-segment millirobot with the phase difference constant between fully functional segments.

For all of the cases where the number of broken segments in a row is less than $n_{critical}$, the difference between using the nonexistent gait and not altering the gait was small, as can be seen by examples of these cases in Fig. 9 and Fig. 10. This suggests that it may not be beneficial to have additional sensing and control to alter the gait when static stability is not compromised; however, it is also conceivable that there is a different, optimal method of altering the gait that may result in increased performance. The nonexistent gait was merely chosen based on the idea that keeping a small constant phase between functional segments may assist in retaining beneficial undulations.

B. Static stability compromised

If more than $n_{critical}$ segments in a row or the first or last segments are broken or missing, altering the gait is necessary to maintain static stability. Two strategies were used for this:

1) Nonexistent gait: A phase of $\frac{360}{n-(n_m+1)}$ degrees, which is constant between fully functional segments, is used, where n_m is the number of broken segments. This is the same as the nonexistent gait for when static stability is conserved.
2) Nonconstant gait: The nominal optimal undulatory phase of $\frac{360}{n-1}$ degrees is retained between all segments, except the segment immediately following the group of more than $n_{critical}$ broken segments, which is altered to be 180 degrees out of phase of the segment immediately before the group of broken segments. This relies on the idea that static stability can be maintained as long as the phase between segments surrounding a group of broken segments is not more than 180 degrees.

Both of these strategies are illustrated in Fig. 7(b).

TABLE I
TOTAL BODY ROTATION θ AND LEG ANGLE α (DEGREES) DURING A STEP AVERAGED OVER 20 STEPS AT 15HZ

Nominal Segments	Broken Segments	Gait	$\Delta\alpha$	$\Delta\theta$
6	3rd and 4th	Nonconstant	12.8	-2.9
6	3rd and 4th	Nonexistent	15.1	1.3
7	3rd, 4th, and 5th	Nonconstant	11.5	-4.7
7	3rd, 4th, and 5th	Nonexistent	18.8	0.2

In the four experimental cases in which static stability was compromised, the nonexistent gait resulted in significantly higher speeds than the nonconstant gait, particularly at higher frequencies (Fig. 8). An example plot of the nonexistent and nonconstant gaits for a 7-segment robot with the 3rd, 4th, and 5th segments missing is shown in Fig. 10. The nonexistent gait caused a v_d of only 18 and 32 percent at 15 hz for 2 segments in a row missing for a 6-segment robot and 3 segments in a row missing for a 7-segment robot, respectively. This shows that even when more than $n_{critical}$ legs are missing, locomotion is still possible with only a small degradation in performance so long as the gait is altered. The nonconstant gait was chosen for its simplicity, only requiring one drive signal to be altered, while the nonexistent gait was chosen since the constant phase between functional segments was expected to assist in preserving body undulations. This was found to be the case when tracking the average leg and body rotation for both gaits for two cases at 15 hz. As shown in Tab. I, the nonexistent gait results in an average positive body rotation and larger leg swing compared to the nonconstant gait.

VIII. EFFECT OF LOCATION OF MISSING LEGS

Example cases were used to examine effects of the location of missing legs on v_d. If a particular segment or group of segments cause more of a decrease in speed when broken, it may be beneficial to have sensors on only those segments to alter the gait and avoid performance degradation or critical failure.

Fig. 9 shows that the location of the missing legs along the length of the body has no noticeable effect on v_d for millirobots with 5, 7, and 10 segments across the entire range of frequencies, except when the last segment is missing. Conversely, the 3-segment millirobot presents a unique problem

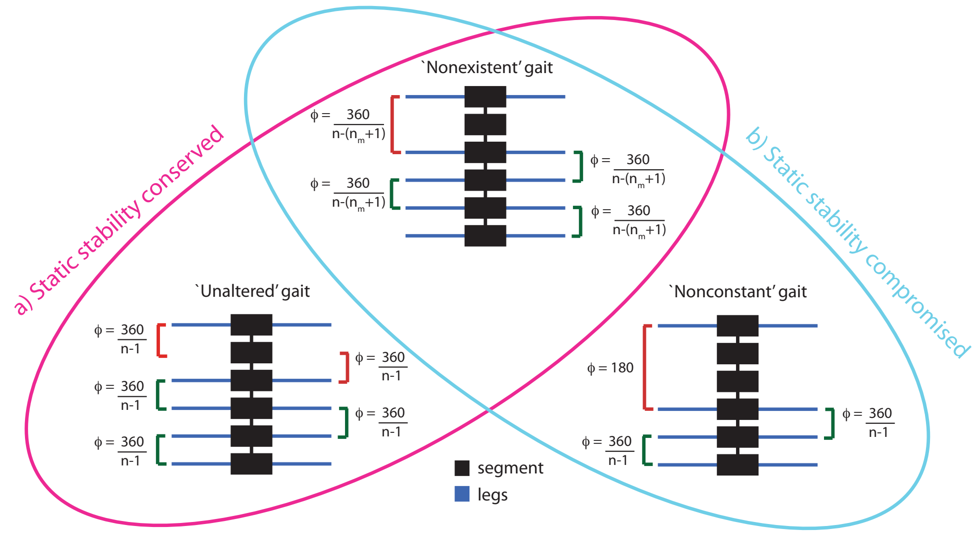

Fig. 7. An illustration of the different gaits that were tested when static stability is a) conserved and b) compromised. The unaltered gait does not alter the phase between segments from the nominal undulatory gait when legs are removed, while the nonexistent and nonconstant gaits both alter the phase between segments as legs are removed.

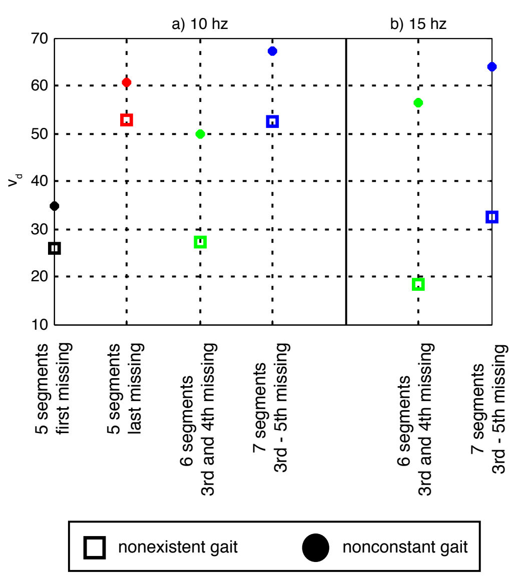

Fig. 8. Percent decrease in speed when static stability is compromised.

in terms of location of missing legs. As the first and last segments are in phase, if the middle segment loses both legs, catastrophic failure occurs unless the gait is altered to make the first and last segments 180 degrees out of phase. This causes a dependency on location of missing legs for the 3-segment millirobot, but not for millirobots with 5 or more segments.

While the location of missing legs along the length of the body did not affect millirobot speed, the number of segments in a row with missing legs did have a significant effect on performance. As can be seen in Fig. 10, even with the same number of missing legs, having more broken segments in a row causes a more significant decrease in speed, independent of drive signal. When legs are missing, the body tends to sag due to the passive body compliance. This problem is exacerbated when many legs in a row are missing as the serial compliance in the body causes increased deformation. In addition to loading segments adjacent to the group of missing legs, the resulting body curvature also causes segments further from the group of missing legs to lift off the ground, thus decreasing their contribution to forward locomotion. This is illustrated in Fig. 11. The only observed exception to this was with 6 segments when there was no noticeable difference in speed between the 3rd and 5th segments legs missing and the 3rd and 4th segments legs missing using the nonexistent gait.

A 10-segment millirobot has shown that with four or more segments in a row missing, the body sags to the extent that segments with missing legs touch the ground. While the static stability analysis in Sec. III suggests that millirobots with 11 or more segments can have 4 broken segments in a row while still maintaining static stability, the off-axis compliance of the body is the limiting factor. While it has been shown that a passively compliant body allows for locomotion enhancing undulations and the off-axis compliance may help in preserving ground contact of all legs when traversing rough terrain, there may be a trade-off when considering cases when many legs are missing.

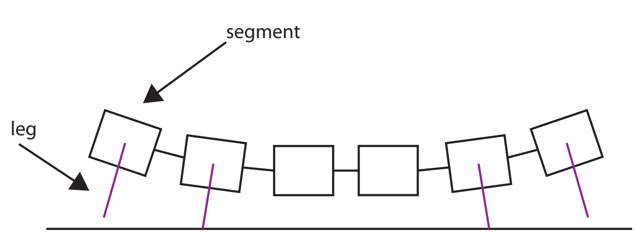

Fig. 11. An illustration of the resulting body curvature when groups of segments have missing legs.

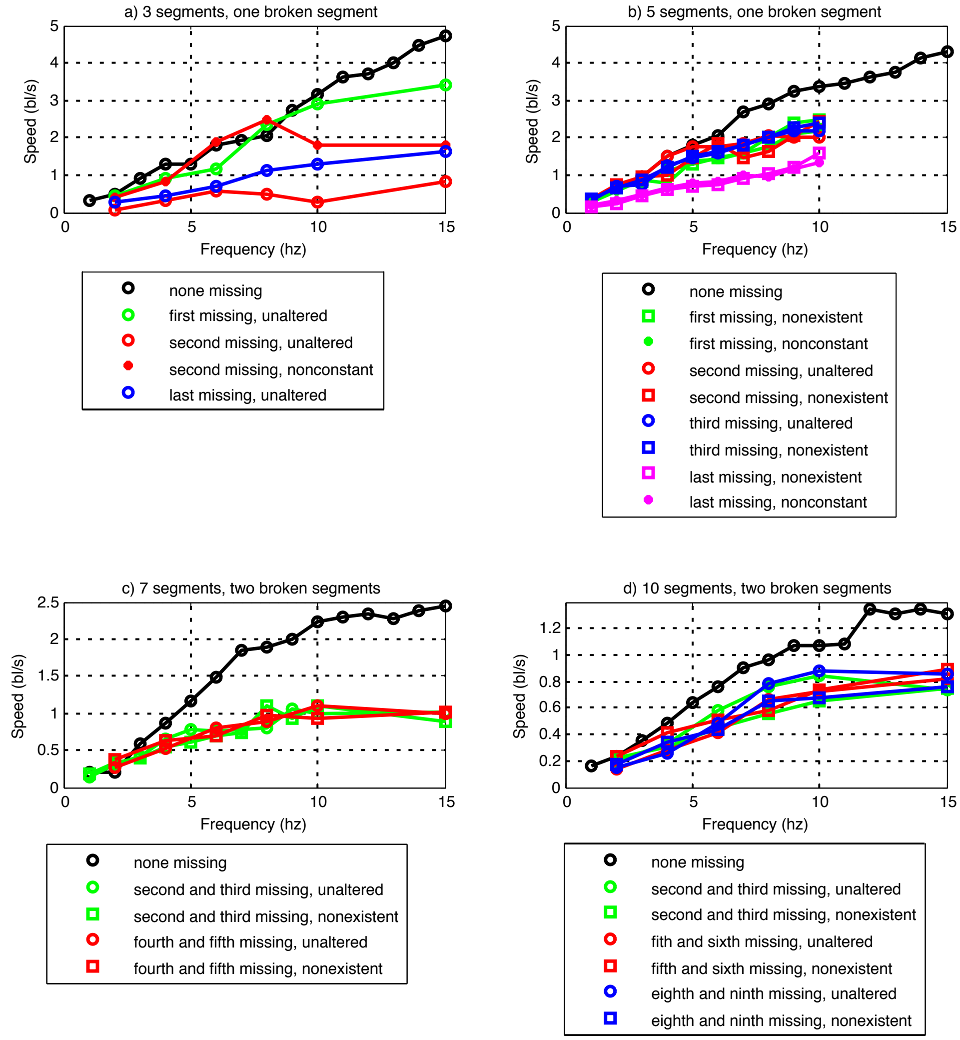

Fig. 9. Speeds for 3, 5, 7, and 10 segment millirobots showing that the location of missing legs along the length of the body does not affect performance for similar numbers of missing legs. The exception is with the last segment.

IX. CONCLUSIONS

This paper describes the effects of mechanical redundancy as a method for robustness to failures in miniature underactuated robots. A kinematic analysis showed that $floor(0.5(n-3))$ segments in a row can be damaged before an n-segment millirobot loses static stability while using the optimal undulatory gait. While the speed of forward locomotion decreased as legs were removed, there was a graceful degradation without altering the gait. Robustness of locomotion to leg failures didn't increase as a function of nominal legs when considering the percentage of legs lost; however, millirobots with 6 or more segments were found to experience less of a decrease in speed than 3 or 5 segments when considering the absolute number of missing legs. If the expected number of failures is a sublinear function of the nominal number of segments, there is an advantage to having more legs.

It was found that when less than $n_{critical}$ segments in a row were missing and static stability was conserved, there was no benefit to increasing the phase between working segments to account for the missing legs. For cases where static stability was compromised, the nonexistent gait resulted in better performance over the nonconstant gait; however, the off-axis compliance in the millirobot limited the number of legs that could be missing in a row even when the gait was altered.

X. ACKNOWLEDGEMENTS

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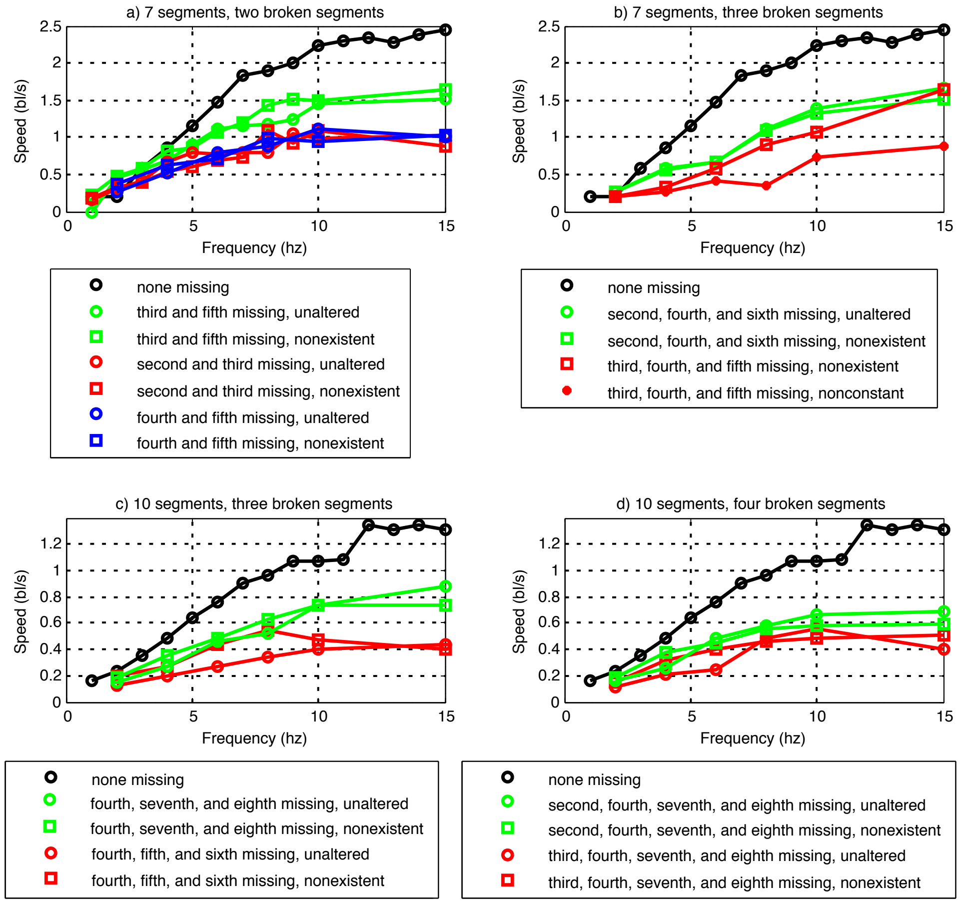

Fig. 10. Speeds for 7 and 10 segment millirobots illustrating that multiple segments in a row missing (red and blue), as opposed to missing segments distributed along length of body (green), results in a greater decrease in speed compared to baseline speeds (black).

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