Concept Design of Reproductive Worm Robot: A Natural Inheritance of *C.elegans* Biological Worm

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Abstract: Although research in the field of worm robotics has taken some stride in recent past, the connotation of such designs was missing the feel of biology in true sense hitherto. Design and firmware of bio-inspired robots have been attempted by several research groups globally but none of those seriously intrude different physiologoical systems of the said biological specimen. Our attempt on technology-driven ideation of the reproductive system of a celebrated biological worm, namely, *Caenorhabditis elegans (C.elegans)* has culminated into concept-designs of Reproductive Worm Robot. Incidentally, *C.elegans* is an interesting biological entity that evokes imagination and assertion to create miniature robotic systems, especially by mimicing its reproductive system. In this paper, we have reported the technological concept designs as well as part-hardware of the working prototype of representative Reproductive Worm Robots by naturally inheriting the reproductive mechanism of the biologocal *C.elegans* worm (notwithstanding the size effect).

Keywords: Worm, C.elegans, Robot, Miniature, Reproductive system, Mechanism, Biology, Mother-Daughter, Bio-inspired robotics.

1. INTRODUCTION

The vast domain of Bio-inspired Robotics has been nourished with several key-themes of design over the years and those are, no doubt conceptually briliant. The size effect of such bio-robotic gadgets was also tackled through modern-age manufacturing as well as assembly technologies and we have got experimental gadgets like worm robots as outcome. However, in all such prototypes of miniature bio-robots and/or worm robots the essence of biological science was missing till date. This was not uncalled for because no coherent approach was put forward globally to take care of the biological nittygitties of the creature(s), except two research simulation initiatives as part of '*Worm Robot Project*' (took off in 2004 in Hiroshima, Japan and subsequently in 2005 in Texas, USA using 1-wire network simulator), barring the earlier informal attempt (in 1998) by a group of Japanese researchers. These maiden attempts of sensor-based simulation were criticized for not being biologically realistic despite having full structural connectome to *Caenorhabditis elegans (C.elegans)*. Finally, the *OpenWorm* project was launched in 2011 as world's first detailed biophysical simulation of the nematode *C.elegans*, focusing on the development of neoro-computational software (*www.openworm.org*).

Incidentally, the global project on developing 'worm robot' was conceptualized after studying the amazing nervous system of the minaiture biologiocal creature, *C.elegans*. Technologists took the stride in articulating the first prototype of the 'worm robot' with an inspiration from the anatomy of *C.elegans* that houses 302 neurons in a tiny volume of 0.002 mm^3 (~$2x10^{-6}$ cc), with an ensemble body-length of only 1 mm. Although the thematic of *OpenWorm* project' was quite novel, yet the main thrust of the project was on development of robotic sensory systems in the form of tiny 'taxels', equivalent to the said 302 neurons. Hence, the project was not tuned to the mechanical design aspects by mimicing various physiological systems of *C.elegans*.

Besides global 'worm robot projects', basic research as well as prototyping of miniature 'worm-like' robot have commenced at various research laboratories in the past decade. As a matter of fact, "Worm Robotics" has started establishing itself as an emerging domain of Bio-Robotics research that is gaining popularity due to its long-standing varied applications. These end-applications are mostly in social sectors, rescue operations, maintenance services and home uses. In nutshell, we can christen the domain of "Worm Robotics" as a novel form of sub-miniaturized "Bio-Robots", wherein we need to play around a dimension in the range of milli-meter or even less in some cases (if suitable manufacturing / fabrication method supports).

Factually, a majority of worm robotic research activities have concentrated the effort towards stabilizing run-time dynamics of the system. By this yardstick, the important paradigm of biological inheritance quotient of the *C.elegans* has been practically sidetracked till date. Biological inheritence of

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natural nematodes has resulted in few interesting bio-robotic designs in recent past. Although study on locomotion of a representative bio-inspired robot, such as snake was an effective prelude (Hirose, 1993), more emphasis was put in for mimicking limbless locomotion, *e.g*. crawling & swimming, as well as neuro-muscular modeling thenafter (Guo & Mahadevan, 2008), (Hirose & Yamada, 2009), (Stirman *et al*, 2011), (Leifer *et al*, 2011), (Butler *et al*, 2015). Recently, a specific light-weight fabric has been used for prototyping a worm robot, resembling the peristaltic locomotion of earthworm (Anna Mehringer, 2017). As biological earthworms are skilled for navigating in a confined volume, the soft robotic counterpart (*Fabricworm*) is poised to exploit the mechanism of peristaltic locomotion to achieve sound surveillance tasks, such as pipe inspection or rescue operations. The intrinsic property such as limited stiffness was exploited to build either a continum trunk-type robot (Bartow *et al*, 2014) or a continum worm-like robot with decentral control architecture (Eder *et al*, 2014) or a compilant modular worm-like robotic mechanism that used anthromorphic properties for the control system (Martin Eder, 2015). The research expertise so developed, has led to prototyping bio-inspired micro-robots in recent past (Palagi & Fischer, 2018), (Rus & Tolley, 2018), (Sitti, 2018).

In contrast to the conceptualization of *C.elegans*-based robot worm, research was carried out by some research-groups for the micro-manipulation of *C.elegans* nematodes in the laboratory, aided by robotic system(s). Rigorous experiments were done with 240 worms at an injection rate of 6 worms per minute using custom-built robotic device (Xianke Dong, 2019). Innovative microfluidic type robotic device was designed and fabricated for the purpose of real-time morphologic measurement & sorting of *C.elegans* (Dong *et al*, 2019). Further, fuzzy-PID control system was invoked for such robotic microbiomanipulation (Zhang *et al*, 2017). Concept, postulations & practical implementation of robotic micromanipulation of cells and small organisms were reported as well (Dong *et al*, 2015a). Novel robotic devices were prototyped for high-speed micro-injection, age synchronization & micro-manipulation of bulk *C.elegans* (Dong *et al*, 2015b,c,d).

The morphological computation of compliant bodies established a strong foundation for the working prototypes of worm-like robots (Hauser *et al*, 2011), (Hauser *et al*, 2012). Extensive studies have been accomplished on the kinematic & dynamic modeling of complaint continum robots in order to establish the locomotion paradigms (Jones & Walker, 2006), (Webster & Jones, 2010), (Mahl *et al*, 2012), (He *et al*, 2013), (Mahl *et al*, 2014).

On the other hand, the mechanism of locomotion and manipulation of soft robots were investigated as well from the perspective of bioinspired modeling of octopus towards providing a viable technology-solution (Calisti *et al*, 2011), (Mazzolai *et al*, 2012). Likewise, considerable research effort was put forward for prototyping modular snake-robot (Melo *et al*, 2013). In contrast to the modular design approach for a fully compliant or soft structured body (Onal & Rus, 2012), intrinsic properties of tensegrity structures were exploited for such micro-locomotion of bio-robots (Caluwaerts *et al*, 2013).

The fundamental concept of developing Reproductive Worm Robot ($\boldsymbol{R^2}W$) or in short, '*ReproWorm*' lies with the biological facet of '*Mother*' & '*Daughter*' worm. In other words, the basic *ReproWorm* will be the '*Mother*' and it will have technological provision for 'delivering' the '*Daughter*' robot-worms in a time-bound manner following a pre-assigned sequence for such 'delivery'. As mentioned earlier, our indigenous design architecture of '*ReproWorm*' has evolved by getting inspiration from the famous biological worm *C. elegans*. The generic concept of R^2W is rooted with the ideation of 'Reproductive Sack' (*RS*) that is pretty similar to situations of biological worm. In our specific case with *C.elegans*, this notion of reproductive sack has been mutated through a novel design of robotic encapsulation, wherein multiple off-springs of R^2W can be obtained sequentially. However, unlike the case of reproduction of biological *C.elegans*, we can't have a smooth transition of the robot worm off-spring in the surrounding environment, because those '*daugther*' robot-worms are not 'live' worms. Hence, we need to augment the technology for near-smooth 'falling' of the robotic off-sprimgs over the ground ('datum') surface. Ideally the '*mother*' *ReproWorm* should be positioned suitably over the datum so as to ease out the 'reproduction' process, technologically. Irrespective of the static position of the '*mother*' *ReproWorm*, the said robotic reproduction process will generate enough vibration in the system, which is inevitable but can be controlled via tailor-made technology.

With this background theology, we shall address the design attributes of a representative *C.elegans* Worm based Reproductive Robot (*CeWReR*) in this paper. Concept-wise, two generic groups of *CeWReR*s will be detailed out having variations in 'reproductive sack'. However, design of the '*daughter*' *CeWReR*s will be identical in these two generic types and those will be independent of the overall disposition of the 'reproductive sack'. The conceptual facets and detailed schematic design of the *CeWReR*s, as postulated in this paper, can be entrusted to usher in successful prototyping of the *ReproWorm* in due course.

The paper has been composed in seven sections. The relevant biological paradigms of the live *C.elegans* worm have deen delineated in the next section, with focused emphasis on its reproductive system. A comparison has been brought out between the technological transform metrics of the proposed *ReproWorm* and the reproductive biological system of the live worm in section 3. The conceptual metrics of the *ReproWorm* are discussed in section 4 and the details of the feasible design schemes of the targeted *ReproWorms*, *i.e*. *CeWReR*s have been reported in section 5. Section 6 addresses the experimental verification and synthesis of the engineering design of the *CeWReR*s. Finally, concluding remarks are made in section 7.

2. BIOLOGY OF *C.ELEGANS* WORM REVISITED

Caenorhabditis elegans (*Caeno*, recent; *rhabditis*, rod; *elegans*, nice) is a very special type of nematode (round worm) that resides in the soil in natural habitable conditions. This free living, non-parasitic transparent soil nematode came on the genetics scene in 1963 when Sydney Brenner introduced it as a model organism for perusing research in developmental biology and neurology (Brenner, 1974). It gained attention of the researchers quickly because the simple genetics and quick life cycle of this worm make it an attractive model to study gene functions; in addition, it is easy and cost effective to rear in the laboratory. Apart from simple genetics and fast life cycle, *C.elegans* worm possesses many attractive features that allow scientists to exploit the creature further in order to answer many fundamental questions related to functioning of a living system. *C.elegans* was the first multi-cellular organism to have its whole genome sequenced, and as of 2022, is the only organism to have its connectome (neuronal "wiring diagram").

The external physical disposition of *C.elegans* is indeed astonishing~ this very worm is 1 mm. in overall length in adult stage and has a tapered cylindrical exterior. This tapering is at both ends and the basic slim cylindrical body of the worm it is about 50 microns in diameter. Figure **1** shows the external envelope of an adult *C.elegans* worm under natural posture for its locomotion [image was captured with a *Hamamatsu Orca*® *R2* camera on an inverted *Olympus*® *IX81* high-resolution microscope using a 60× oil objective (NA 1.42)]. The various internal organs and physiological systems of an adult *C.elegans* are labeled in Figure **2**. This diagram serves as fundamental conceptualization metric for our indigenous 'Reproductive Worm-Robot'.

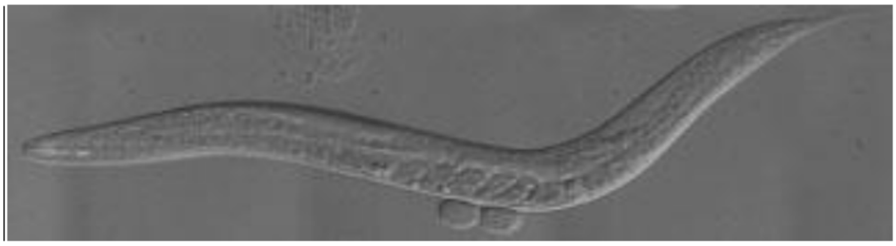


Figure 1: External Envelope of an Adult *Caenorhabditis elegans* Worm.

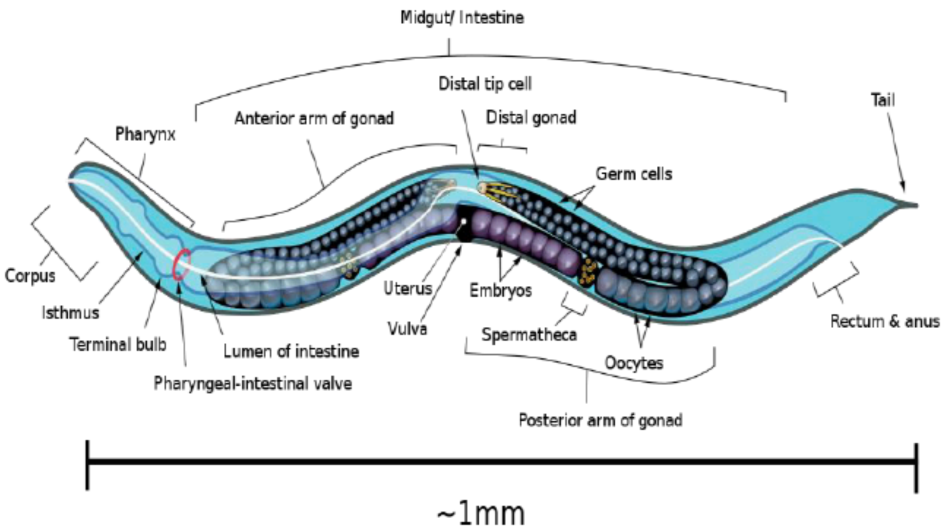


Figure 2: Internal Organs & Physiogical Systems of an Adult-stage *Caenorhabditis Elegans.*

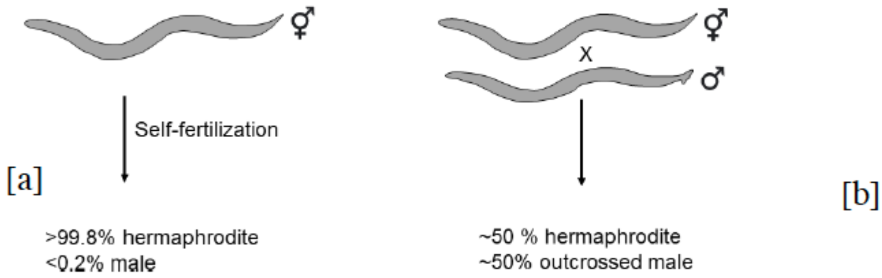


Figure 3: Schematic Diagram of the Reproduction Process of Biological *C.elegans.*

The adult *C.elegans* has two sexes, namely, hermaphrodite & male. Accordingly, the natural reproduction process of *C.elegans* occurs via two ways, viz. a] self-fertilization & b] mating (refer Figure **3**). In both cases, fertilization is the prime process in sexual reproduction of an adult *C.elegans*. Primarily it exists in nature as a self-fertilizing hermaphrodite that produces less than 0.2% male (Figure **3a**). On the other hand, male *C.elegans* have specialized tails for mating that include spicules. When the hermaphrodite mates another male, they produce almost 50% male as outcrossed progeny (Figure **3b**).

It is interesting to note that spermatogenesis and fertilization process in *C.elegans* take place in three different forms. The schematic representation of the overall process of reproduction is presented in Figure **4**. The diploid (2n) primary spermatocyte undergoes three rounds of cell divisions via secondary & terminal spermatocyte to produce four haploid (n) spermatids (Figure **4a**). The inactivated spermatid undergoes morphological changes to form activated spermatozoa (Figure **4b**). The final fertilization episode is depicted in Figure **4c**, wherein only one sperm (shown with 'arrow') enters into the oocyte during fertilization in order to send the signal to the oocyte to complete meiosis cell division and subsequently undergoes mitotic division.

By and large, the reproductive cycle of *C. elegans* encompasses internal fertilization with sub-processes like sperm activation within the reproductive tract, oocyte meiotic maturation, polyspermy block to activation and degradation of selected maternal mRNAs (Horner & Wolner, 2008), (Matthew *et al*, 2010), (Madl & Herman, 1979), (LaMunyon & Ward, 1998). Like all sexually reproducing organisms, the presumptive female gametes in *C. elegans* also undergo meiotic maturation prior to fertilization (Dent *et al*, 2000), (Robertson & Lin, 2013). The oocytes of most animal species arrest in meiotic prophase I and, in response to intracellular signalling, they complete meiosis (meiotic maturation). The signal that triggers oocyte maturation in *C. elegans* is secreted by the sperm, and is termed Major Sperm Protein [MSP] (Miller *et al*, 2001). In addition to promoting oocyte maturation, MSP also induces gonadal sheath contraction, which pushes the oocyte through the spermatheca for fertilization. It is proposed very recently that MSP might be involved in interacting oocyte components after fertilization (Banerjee & Srayko, 2022).

3. TECHNOLOGICAL TRANSFORM METRICS BETWEEN BIOLOGICAL *C.ELEGANS* & ROBOTIC WORM

As we have revisited the pathways of reproduction of the biological *C.elegans,* especially through Figures **3** & **4**, it is becoming aparent that the gradual process of transformation from biology to technology needs

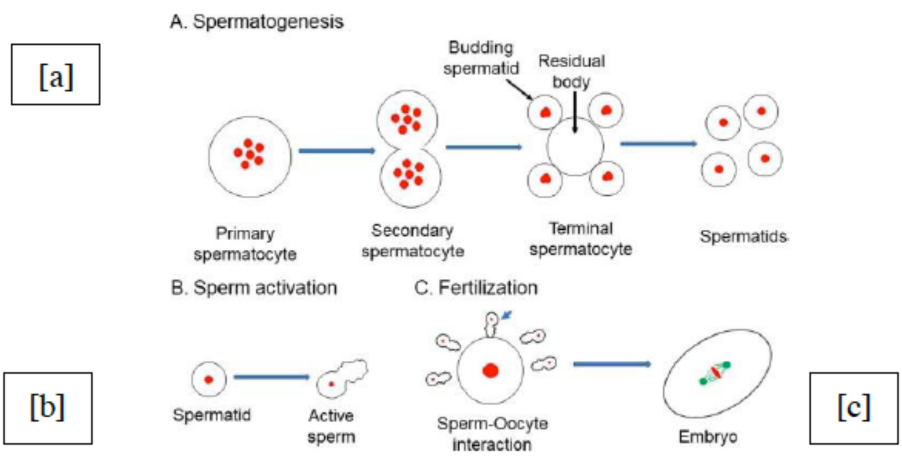


Figure 4: Schematic Representation of Sperm Activation and Fertilization Process in *C. elegans.*

subtle mentoring. If we scrutinize the biological paradigms of the reproductive system of *C.elegans* worm, we will be able to distinguish those into two broad verticals, namely: [a] features those can be reproducible technologically, *i.e*. *coherent features* and [b] features those need to be modulated to fit in the technology manifold, *i.e*. *non-coherent features*. It is obvious that so-called 'technology manifold' of the biological *C.elegans* is nothing but the desired ensemble of *ReproWorm*. The *features*, whether biological or technological, have a direct one-to-one mapping between the representative states. This mapping is indeed interesting and it gives a clear-cut idea about the so-called robotic transform of *C.elegans* worm in real-time. The major facets of the biological reproduction process of *C.elegans* are: *sperm*, *oocyte*, *MSP* and *mRNAs*. Considering the biological notions of these four facets a-priori, we can summarize the following one-to-one mapping for the technolgical counterparts: i] *Sperm* → Sensors of the '*daugther*' worm robots; ii] *Oocyte* → Prime-movers of the '*daugther*' worm robots; iii] *MSP* → Resistive circuits / *Wheatstone bridge* inside the sensors; iv] *maternal mRNAs* → fusion of sensory signal of the '*daugther*' worm robot(s). As corollary of [i], 'immobile, fertilization-defective sperm' can be mapped as malfunctional sensor of the *ReproWorm* (either '*mother*' or '*daugther*' or both). In nutshell, the entire mapping has a bias towards sensory augmentation of the *CeWReR*-prototypes. Table **1** presents a comparative parallel between major biological features of *C.elegans* and corresponding technological features of the *Robo Worm*.

It may be observed from the table above that substantial features are highly coherent between biological *C.elegans* and *ReproWorm*. In fact, out of 27 features that have been listed, 19 are coherent, *i.e*. nearly 70.4%. that clearly indicates viability of the design of our proposed *ReproWorm*, *CeWReR*.

4. CONCEPTUAL DESIGN METRICS OF THE PROPOSED REPRODUCTIVE WORM ROBOT

4.1. Motivation Behind the Proposed Design

Biological *C.elegans* can multiply very quickly by virtue of the well-developed reproductive system. In order to capture this very feature of the biological worm into its robot counterpart, the first design paradigm needs to be ideation on generation of off-spring worm robots using suitable mechanism. Thus the motivations behind the proposed design of a reproductive worm robot are essentially the following: a] shape & size of the off-springs; b] carrier-volume; c] location of the off-springs before being ejected out; d] mechanism of ejection ~ fee-fall vs. rolling; e] stabilization of the off-springs over a robust datum. It may be noted that all of these facets are, by default, natural in case of biological worm and things are pretty chronological. However, we need to think meticulously on all the aspects, stated above, for the proposed transformation to engineering design of reproductive worm robot. The ensemble design-effort is the true motivation for this work so as to obtain a near-feasible replica of the biologocal C.elegans with the capacity of reproductiion, although finite. This sort of reproductive worm robot will find wide applications in various domains such as agriculture, relief & rescue, indoor surveillance etc., wherein availability of off-spring robots will be helpful in performing the tasks neatly.

4.2. Ideation and Analytics of '*Mother*' and '*Daughter*'

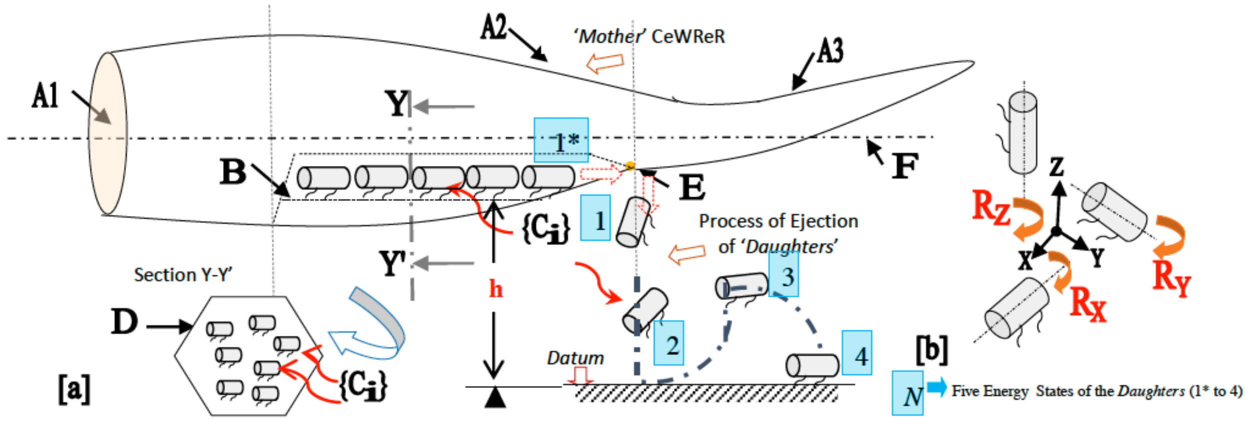
The fundamental impetus behind conceptualization of Reproductive Worm Robot ('*ReproWorm'*) is to have two nearly identical robotic systems, viz, '*mother*' & '*daughter(s)*'. Both of these groups are equally important from the point of view of technology as well as biological parlances. The first & foremost technological paradigm of *ReproWorm* was the 'reproductive sack' that was conceptualized to house the '*daugther(s)*'. The basic thought process for designing the unit was borrowed from the physiological aspects of *C.elegans*; however, the same was modified to a requisite extent for finetuning the engineering design. The conceptual bridging between the biological framework of *C.elegans* worm and its gradual transformation towards engineering (robotic) system is illustrated in Figure **5**. The ensemble ideation of Figure **5** is thus significant, so far as the final scheamtics of *CeWReR* is concerned. Figure **5** is conceptually divided into two parts, viz. [a] & [b], which represent respectively the 'cause' and 'effect' of the formation of *ReproWorm*. Figure **5a** shows an artist's view of the concept of 'reproductive sack' for the *CeWReR* and the nascent process of 'release' (ejection) of '*daughter*' worm(s) from '*mother*' over a pre-fixed elevated datum. Hence, in a way, Figure **5a** symbolizes the perspective or *cause* behind the creation of *ReproWorm*. It may be noted that both '*mother*' & '*daugther(s)*' should share the common datum (horizontal plane) in order to ensure better stability of the dual system in real-time operations. However, if situation demands, '*mother*' can be at a slighly elevated surface, as in the case of Figure **5a**. The process of ejection of '*daughters*' is finite and fundamentally it is related to omni-directional rotation and/or twist of the '*daugthers*' in 3D space. This self-rotation of the *CeWReR-daughters* can be around any axes (X,Y,Z) at random. The schematic of this very rotation is illustrated in Figure **5b**.

Table 1: Comparison of Biological Features of *C.elegans* and Technollogical Aspects of Reproductive Worm Robot

Sl. No.	Biological Feature	Technological Paradigm	Remarks
1.	<u>*Natural Existence of C.elegans*</u>: As a self-fertilizing hermaphrodite.	<u>*Natural Existence of ReproWorm*</u>: It is able to produce a fixed number of '*daughter*' worm robots of its own.	*Coherent Feature*
2.	<u>*Stages for Adulthood*</u>: Both male and hermaphrodite progress through four larval stages to become adult.	<u>*Stages for Adulthood*</u>: The '*daughters*' do not pass through any morphological alterations. Those are produced in full prototype ('adult').	*Non-coherent Feature*
3.	<u>*Tracking of Cells:*</u> Fate of each and every somatic cell of *C.elegans* can be tracked for biological experimentations.	<u>*Tracking of the Prototype*</u>: Each & every sensory unit of the '*daughter*' worm robot can be tracked separately for troubleshooting.	*Coherent Feature*
4.	<u>*Chances of Fertilization:*</u> Fertilization is not always certain in *C.elegans* and attainment of adulthood.	<u>*Ejection of 'Daughter' Robots:*</u> All 'daughter' worm robots are identical and equally likely to emerge from the '*mother*' robot.	*Non-coherent Feature*
5.	<u>*Development of the Off-springs:*</u> The outer epithelial layer of the epidermis secrets the extra cellular matrix that forms the outer layer of the body of the off-springs.	<u>*Development of the 'Daughters':*</u> Unlike *C.elegans*, '*daughter*' worm robots are made ready for ejection in totality inside the hollow internal cavity of the '*mother*' robot.	*Non-coherent Feature*
6.	<u>*Metamorphosis of Embryo*</u>: The epididymis of the embryo needs to undergo a series of cell fusion events.	<u>*Metamorphosis of 'Daughter:*</u> Each '*daughter*' worm robot must have robust sensory data fusion algorithm and instrumentation for effective actuation after its ejection.	*Coherent Feature*
7.	<u>*Types of Fertilization*</u>: Spermatogenesis and fertilization process in *C.elegans* take place in three different forms.	<u>*Types of 'Daughters':*</u> The '*mother*' *ReproWorm* can eject in two design-forms, viz.: either 3 or 4 '*daughters*' at a specific time.	*Coherent Feature*
8.	<u>*Nature of Fertilization*</u>: By and large, the reproductive cycle of *C. elegans* encompasses internal fertilization.	<u>*Nature of 'Reproduction'*</u>: The '*daughters'* reside fully inside the sack of the '*mother*', under an openable joint-actuated covering (membrane).	*Coherent Feature*
9.	<u>*Activation of Sprem*</u>: Sperm activation happens within the reproductive tract of *C.elegans*.	<u>*Activation of 'Daughter':*</u> The sensory processing of '*daughter*' worm robots get functionalized inside the 'reproductory sack' of the '*mother*' .	*Coherent Feature*
10.	<u>*Maturation of the Oocyte*</u>: Oocyte of *C.elegans* follows a systematic time-bound process of meiotic maturation.	<u>*Maturation of the 'Daughter'*</u> The '*daughter*' worm robots do not need any 'maturation' as such, because those are in fullest composition inside 'mother' *ReproWorm*.	*Non-coherent Feature*
11.	<u>*Denial of Polyspermy*</u>: Adult C.elegans block polyspermy to happen and it resists such activation.	<u>*Denial to Multiple 'Daughters'*</u>: The '*mother*' *ReproWorm* blocks poluspermy and confirms that only pre-defined number of '*daugthers*' get ejected out at a desired time-instant.	*Coherent Feature*
12.	<u>*Neuron Activation for Oocyte:*</u> Selected maternal mRNAs get degraded.	<u>*Activation of Sensory System:*</u> *ReproWorm* needs perfect fusion of sensory signals before as well as after the ejection of '*daughters*'.	*Coherent Feature*
13.	<u>*Reproductive Variants*</u>: Both varieties of C.elegans, namely, males and hermaphrodites perform spermatogenesis.	<u>*Reproductive Variants*</u>: Both variants can accommodate a pre-defined number of '*daugther*' worm robots in healthy & active form.	*Coherent Feature*
14.	<u>*Sustenance of Oocyte*</u>: Hermaphrodite C.elegans germs cells stop spermatogenesis after fourth stage of embryonic growth.	<u>*Sustenance of the 'Daughter' Robots:*</u> Since '*daughter*' worm robots are self-sufficient in number, locomotion, sensory processing, there is no need for additional technology for sustenance.	*Non-coherent Feature*
15.	<u>*Identical Progeny*</u>: Hermaphrodites can produce self-progeny by using their own sperm.	<u>*Identical Progeny*</u> '*Mother*' & its''*daughters*' can share wireless sensor-based communication and those signals are nearly identical.	*Coherent Feature*
16.	<u>*Preference for mating of Sprems*</u>: The male sperm is preferentially being used because the larger male sperm gain an advantage by crawling faster to outcompete smaller hermaphrodite sperm.	<u>*Preference for Design of 'Daughters':*</u> The creation of '*daughter*' worm robots is fully design-based. Manufacturing process plays an important role in developing the firmware of '*daugther,*' devoiding preferential attributes.	*Non-coherent Feature*

17.	*Maturation of Sprem*: Within the hermaphrodite, the immature male sperm goes through a final maturation process known as spermiogenesis.	*Maturation of 'Daughters':* The functioning of the '*daughter*' worm robots (through D.C. motors) get fully checked prior to the ejection. Any operational problem gets rectified before ejection, if noticed at that time.	*Coherent Feature*
18.	*Activation of Sprem*: In hermaphrodite C.elegans, sperm gets activated when the first unfertilized oocyte progressed through the spermatheca.	*Activation of 'Daughter':* The '*daugther*' worm robots get activated as soon as their individual prime-movers (driver-motors) are powered ON.	*Coherent Feature*
19.	*Control of Oocytes*: The oocytes get kargely arrested in meiotic prophase I in response to intracellular signalling.	*Control of 'Daughters':* The prime-movers of the '*daugthers*' are being controlled in complete synchronization with the internal sensors of the '*mother*' *ReproWorm*.	*Coherent Feature*
20.	*Triggering of Oocyte Maturation*: The signal that triggers oocyte maturation in *C. elegans* is secreted by the sperm.	*Triggering of Prime-movers:* All prime-movers of the '*daughter*' worm robots are triggered by the respective encoders and other internal sensors, *e.g.* infra-red sensors of the 'mother' *ReproWorm*.	*Coherent Feature*
21.	*Constitution of Enbryo / Oocyte:* The embryo or oocyte of the *C.elegans* contains Major sperm protein (MSP).	*Constitution of ReproWorm:* _Resistive circuits, inside the sensors of the *ReproWorm,* (either '*mother*' or '*daugther*'), *e.g. Wheatstone Bridge*.	*Coherent Feature*
22.	*Ejection of Oocyte*: MSP also induces gonadal sheath contraction, which pushes the oocyte through the spermatheca.	*Ejection of 'Daughters"* Because of the imbalance of the Wheatstone Bridge circuitry and/or any digital changeover (from '0' to '1' or vice-versa), sensors get activated sequentially and those activated sensors help the prime-movers of the '*daughter'* worm robots to function as desired.	*Coherent Feature*
23.	*Workability of Oocyte*: MSP might be involved in interacting oocyte components after fertilization.	*Workability of Prime-movers:* Fabrication of the resistive circuits (for anlaog sensors) and/or digital read-outs (for infra-red sensors) is very crucial for the actuation of the prime-movers of the '*daughter*' worm robots.	*Coherent Feature*
24.	*Immobile Sprem*: Immobile, fertilization-defective sperm that can not enter the oocyte suggest that sperm play another regulatory role in *C. elegans.*	*Malfunctional Sensors*: Malfunctional sensors can't trigger prime-mover for any activation for obvious reasons, which shows that sensors do play an important role in overall operation of the *CeWReR*s.	*Coherent Feature*
25.	*Completion of Embryonic Stage*: Successful fertilization of activated oocytes results in completion of meiosis.	*Completion of 'Reproduction':* The process of 'reproduction' of *ReproWorm* gets completed with the tiny locomotion of the '*daugthers*' over a horizontal plane.	*Coherent Feature*
26.	*Growth of Embryo*: The fertilized embryo of *C.elegans* undergoes the first mitotic division for perpetual growth till attainment of adulthood.	*Growth of 'Daughter':* Unlike biological worm, *CeWReR*s do not have any further growth, because the 'reproduction' of '*daughters*' happens at 'adult', *i.e*. full working firmware stage only.	*Non-coherent Feature*
27.	*Pre-fertilization Stability of Sprems*: Pre-fertilization competition among the sperm for attaining stability can also potentially influence the outcome of the fertilization.	*Completition among the 'Daughters':* Unlike fertilization process of biological *C.elegans*, the *CeWReR*s do not have amy competition among the constituent sensors, in context to basic ejection as well as stability of the '*daugthers*' thereof.	*Non-coherent Feature*

As shown in the schematic of Figure **5a**, the ensemble of the prototype reproductive worn robot, *CeWReR* has been conceptualized in a tapered torpedo-like structure that has similarity and close synchronization with that of the biological worm, *C.elegans*. This is so because the robotic structure has got three distinguishable units, *e.g.* 'mouth', 'body' & 'tail'. As per our thematic, this structure is called '*Mother*' *CeWReR* as it houses a 'Reproductive Sack' (*RS*: refer 'B' of Figure **5a**) having a tailor-made design. The reproductory chamber is of hexagonal cross-section (refer 'D' of Figure **5a**) that carries pre-fixed number of '*Daughter*' *CeWReR*s, '{C_i}', i=2,3,4…n. It may be noted that the geometry of the central axis (refer 'F' of Figure **5a**) of the *Mother CeWReR* is crucial because it governs the location of the ejection-point, 'E'. The process of ejection of the '*daughters*' is interesting~ primarily it depends on the location of the '*mother*'. In case '*mother*' *CeWReR* is positioned above the datum plane, then the ejection process will involve jerky movements (of the '*daughters*') with rotation. The schematic of Figure **5a** highlights this stationary disposition of the '*mother*' *CeWReR*; although we will discuss in-plane disposition of the '*mother*' also in the next sub-section.



Legends:{**A1, A2, A3**}: *Mouth*, *Body* & *Tail* of the Reproductive Worm Robot ('*Mother*' *CeWReR*); **B**: Reproductive Sack (Chamber) of *CeWReR*; {**C**$_i$}: *CeWReR* '*Daughters*'; **D**: Sectional View (at Y-Y') of 'B'; **E**: Point of Ejection of '*Daugthers*'; **F**: Central Axis of the '*Mother*' *CeWReR*; {**R**$_X$, **R**$_Y$, **R**$_Z$}: Rotations of '*Daugther*' *CeWReR* respectively around X, Y & Z-axis; {**X,Y,Z**}: Cartesian Co-ordinate System

Figure 5: An Artist's View of the Reproductive Worm Robot: [a] Conceptual Layout of Reproductive Sack of 'Mother' Robot; [b] Omni-directional Rotations of the 'Daughter' Robots (post Ejection).

The complementary aspect of the ejection process of the '*daugthers*' is illustrated schematically in Figure **5b**. The process happens with mild to severe vibration as it is essentially a free fall under gravity. The entire process goes through five energy-states (refer *'N'* of Figure **5a**), wherein exchange of energy (potential to kinetic and vice-versa) occurs in order to complete the sequence of motions for the *daughter(s).* The process essentially caters to omni-direction rotation and/or twist of the '*daugthers*' post-ejection, through the pathway from 'E' to the horizontal datum beneath. This rotation is random and it can't be assessed a-priori. However the rotations or the rotary motions can be visualized as individual modules around X, Y or Z axis, namely, R_X, R_Y & R_Z. Analytically, {R_X, R_Y, R_Z} is the rotation envelope of the '*Daughters*'. However, in practical situation of ejection, these rotary motions can occur in mixed mode, *i.e*. conjugate rotations around two or three axes. Although the mechanism of conjugate rotations can cause instability to the '*daughter*' *CeWReR*s, but at the end of the process we assume the ejected '*daughters*' to be stable over the horizontal datum. Analytically, the said jerky motions generate vibration, which is a sort of spiraling jerk that can have two major incarnations, depending upon the nature of ejection. In other words, this in-situ vibration is the *effect* of the formation of *ReproWorm*.

The ejection process of '*daughter*' *CeWReR*s being incidental, it is important to concentrate on the dynamics of such ejection. Let us revisit the conceptual schematic of Figure **5a**, with more attention towards the central axis, 'F'. The disposition of the said central axis is a vital element of the overall study of the run-time dynamics of the *CeWReR* system ('*mother*' & '*daughter*'). The central axis is acting as the fulcrum for the in-situ oscillations of *CeWReR-mother* in real-time, during the process of 'reproduction'. Although the primary source of this oscillation is longitudinal deflection with respect to the central axis, but a part of this vibration / jerk is happening due to the internal transmission of shear force (from *RS* to the inner body). These attributes have been investigated through the schematics of Figure **6** (pertaining to *CeWReR-mother*), which will be the precursor for studying the dynamics as well as modeling of the '*mother*' worm robot.

Since *CeWReR-mother* is stationary, its central axis, *i.e*. A-A' of Figure **6a** is also staionary (static). Hence, axis A-A' can be used for further referencing of the worm robotic system, especially with respect to its dynamics, as shown in Figures **6c**,**d**. Although stationary, *CeWReR-mother* will undergo longitudinal oscillation with low to moderate frequencies before & after the process of 'reproduction' (refer Figure **6b**). In this context, the imaginary axis (refer B-B' of Figure **6a**) that is passing through the point of ejection ('E') can be treated as 'Reference Axis' for further analysis. Nonetheless, 'E' can serve as the de-facto 'origin' of the representative Cartesian axes in 2D plane, as shown in fig. 6a. The neutral (central) axis, A-A' will assume a curved segment upon deflection and the body-specific Cartesian co-ordinate triads {X,Y,Z} of *CeWReR-mother* will also undergo deflection (refer Figure **6c**). The unit vectors thereof, viz. {e_i} (before 'reproduction' process) and {E_i}(during 'reproduction') will symbolize the physical posture of the '*mother*' worm robot, underegoing oscillations due to the jerks as well as shear force at *RS*. The tanget vector dX_0/ds, at an angle θ with the neutral axis, represents the amplitude of the primary oscillation of the body of the *CeWReR-mother*. Nonetheless, the most interesting dynamics will occur during the time of 'reproduction', *i.e*. ejection of the '*daugthers*' in a sequential manner.

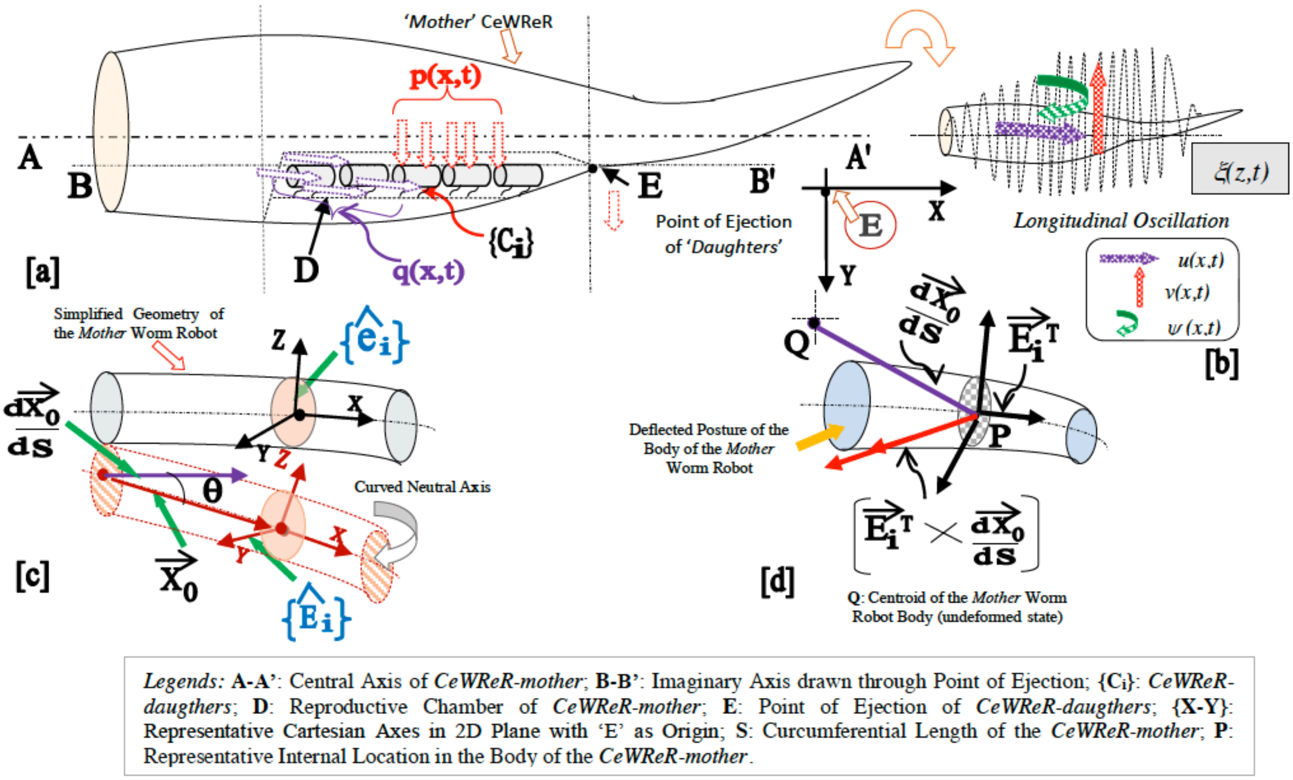


Figure 6: Schematic of Governing Axes and In-situ Oscillation Dynamics of the *Mother* Worm Robot.

Apart from the in-situ self-induced oscillation (represented by $|dX_0/ds|$), the '*mother*' worm robot will experience a shear force per unit cross-section in the quadrature plane. With reference to the schematic of Figure **6d**, the shear force per unit cross-sectional area of the *CeWReR-mother*, *i.e.* E_i^T will try to enhance the amplitude of the oscillation, while the tangential force-vector in the longitudinal plane, viz. dX_0/ds will remain as steady part of the amplitude of the oscillation all through the 'reproduction'.

Hence, by virtue of the conjugate effect of these two force-vectors working in the body of the '*mother*' worm robot, a new vector field gets created ($E_i^T\, dX_0/ds$). As the process of 'reproduction' sets in, this new vector-field becomes instrumental in generating additional jerky motion to the *CeWReR-mother*, over & above its basic in-situ oscillations. The motions of the *CeWReR-mother* considered here are rotation and translation (in the form of deflection), wherein deflections are characterized along axial as well as transverse directions due to the process of 'reproduction'. Thus the ensemble motion-paradigm of the *CeWReR-mother* is essentially a non-linear triad ~ comprising three uncertain functions in space *(x)* & time *(t)*. Out of these, while axial deflection is represented by the unknown function *u(x,t),* unknown deflection in transverse direction is represented by *v(x,t),* alongwith a third component of unknown rotation represented by $\boldsymbol{\Psi}(x,t)$. It may be noted that the non-zero finite transverse and axial distributed loads subjected to the body of the mother-worm robot (due to the ejection process of the daughter worms) are represented by *p(x,t)* and *q(x,t),* respectively (refer Figure **6b**). The dynamics of the near-cylindrical body of the *CeWReR-mother*, as per the schematics of Figures **6c**,**d** has been modeled as a sandwich of Timoshenko Beam Theory & Euler Beam Theory of Classical Mechanics, in order to captrure both the aspects of longitudinal deflection as well as shear deformation of the body of the *CeWReR-mother* during 'reproduction'. The conjugate model of the real-time dynamics of the *CeWReR-mother* is described by the following system of partial differential equations.

To begin with, we will consider the dual of rotation $\boldsymbol{\Psi}(x,t)$ and transverse deflection *v(x,t)*, because these are coupled due to the effect of upward lift of the daughters inside the RS, prior to the ejection. Accordingly, the worm-body dynamics can be modeled as:

$$EI\frac{\partial^2\Psi(x,t)}{\partial x^2}+\Omega GA\left[\frac{\partial v(x,t)}{\partial x}-\Psi(x,t)\right]=\rho I\frac{\partial^2\Psi(x,t)}{\partial t^2} \qquad (1)$$

where, {*E*, *I*, *G*, *ρ*}represent respectively the Young's modulus, Moment of inertia, Modulus of rigidity (shear modulus) and Density of the material of the worm-body; Ω: Coefficient of shear due to the partial occlusion of the reproductory sack; *A*: Average of the cross-sectional area of the three segments of the body of the *mother*-worm, viz. 'head', 'body' & 'tail'; *x*:

Distance along the horizontal plane (plane of ejection); *t*: time-instant.

The process of 'reproduction' will generate a downward thrust over the reproductive chamber as a whole and in result; the transverse load *p(x,t)* over the *mother* worm robot will be compressive in nature. Further, this transverse load will manifest in the transforms for axial deflection *u(x,t)*. Analytically, we can express this compression over the reproductory sack of the *CeWReR-mother* as:

$$EA\frac{\partial^2 u(x,t)}{\partial x^2} - \rho A\frac{\partial^2 u(x,t)}{\partial t^2} = -p(x,t) \quad (2)$$

where symbols '*E*', '*A*', & '*ρ*' bear the usual nomenclature as stated for eqn. 1 above.

In contrary to the manifestation of the transverse load, the axial load *q(x,t)* will be in the form of a horizontal push that will help translating the *daughters* inside the reproductive chamber. Naturally, this phenomenon will be guided by the amount of deflection that the *daughter(s)* will experience in transverse direction [*v(x,t)*], alongwith rotational twist [***Ψ***(*x,t*)]. The functional dependency of the axial load, causing push over the reproductive sack of the *CeWReR-mother* in the horizonal direction, can be expressed analytically as:

$$\Omega GA\left[\frac{\partial \Psi(x,t)}{\partial x} - \frac{\partial^2 v(x,t)}{\partial x^2}\right] + \rho A\frac{\partial^2 v(x,t)}{\partial t^2} = q(x,t) \quad (3)$$

where symbols 'Ω', '*G*', '*A*', & '*ρ*' bear the usual nomenclature as stated for eqn. 1 above.

The ensemble jerking of the body of the *CeWReR-mother*, especially its reproductive sack, is a combination of translational deflection and deflection due to shear force. The parenthesis of this ensemble jerking, *ξ(z,t)* predominantly in the form of longitudinal oscillation (refer Figure **6b**) can be represented mathematically through the fourth-order partial differential equation, combining the non-linearity effect. This conjugate non-linerity in the deflection arises due to simultaneous influence of Young's modulus ('E') & Shear modulus ('G') in the time-domain. By combining the models of *Timoshenko Beam* and *Euler Beam* under one matrix, we propose the conjugate deflection equation for the *CeWReR-mother* as:

$$EI\frac{\partial^4 \xi(z,t)}{\partial t^4} + \rho\frac{\partial \xi(z,t)}{\partial t} + GA\frac{\partial^2 \xi(z,t)}{\partial t^2} = 0 \quad (4)$$

where, symbols '*E*', '*I*', '*G*', '*A*', & '*ρ*' bear the usual nomenclature as stated for eqns. 1 & 3 above.

The functional paradigm of the ensemble jerking will take the following form:

$$\xi(z,t) = \xi(z)Cos(\omega t) + \mu(\omega t) \quad (5)$$

where, '*ω*' is the natural frequency of vibration of the *CeWReR-mother* and '*μ*' is the co-efficient due to shear force that is attributing additionally to the natural frequency. Finally, the time-spanned variation of the oscillation amplitude of the body of the *CeWReR-mother* can be expressed analytically as:

$$\begin{aligned} y(t) = A_1Cosh(\lambda.\xi.t) + A_2Sinh(\lambda.\xi.t) + \\ A_3Cos(\lambda.\xi.t) + A_4Sin(\lambda.\xi.t) + \mu.e^{-jt} \end{aligned} \quad (6a)$$

where, '*λ*' and '*j*' are the co-efficients due to longitudinal oscillation and shear-infused jerk respectively. The co-efficients {A_1, A_2, A_3, A_4} can be evaluated numerically through Finite Element Analysis of eqn. 1. The value of '*ξ*' can be determined numerically via eqn. 5 and that of '*λ*' will be obtained through the following mathematical expression, viz.

$$|\lambda| = \frac{(\rho)^{\frac{1}{4}}(\omega)^{\frac{1}{2}}}{(EI)^{\frac{1}{4}}} \quad (6b)$$

Unlike the real-time dynamics of *CeWReR-mother*, the dynamics of the *daughter(s)* is more challenging as that involve dissipation & tranafer of energy-states. With reference to Figure **5**, we can observe five different energy-states for the *daughter(s),* encapsulating the entire episode of 'reproduction', namely state# *1*, 1, 2, 3* & *4*. The potential & kinetic energy of a single *daughter* that is being ejected from the reproductive sack of the mother at different states can be computed. Finally, we can arrive at couple of energy-balance equations, which will be indicative of the state of dynamics for the *CeWReR-daughter*. Table **2** presents the expressions for Potential Energy (P.E.) & Kinetic Energy (K.E.) of the *CeWReR-daughter* at various states (1* to 4).

As detailed under Table **2** above, several energy-balance equations can be solved (for the summation of P.E. & K.E.) at various energy-states, *e.g.* between *'1*'* &*'1'*, *'1'* & *'2'*, *'2'* & *'3'* and *'3'* & *'4'*. Those solutions will lead to the analytical estimation of the natural frequencies of vibration of the *CeWReR-daughter(s)* during the entire process of 'reproduction'.

4.3. Run-time Dynamics of the Ejected '*Daughters*'

Two cases can occur in the study of run-time dynamics of ejection of *CeWReR-daugthers*, namely: *Case I*: *CeWReR-daughters* are ejected vertically (with

Table 2: Analytical Expressions for Potential & Kinetic Energy of *Daughter* Worm Robot during Reproduction

Energy State	Description of the Energy State	Expression for P.E.	Expression for K.E.
1*	*Pre-Ejection*: *Daughter* is inside Reproductive Sack	$(P.E.)_{1*} = mgh = (\pi D_{av}^2 / 4..L).g.h$	$(K.E.)_{1*} = 0$
1	*Verge of Ejection*	$(P.E.)_1 = (\pi D_{av}^2 / 4.L).g.(h - x_1)$	$(K.E.)_1 = \frac{1}{2}\left[mv_1^2 + I\omega_1^2\right]$
2	*Free Fall with Rotation*	$(P.E.)_2 = (\pi D_{av}^2 / 4.L).g.(h - x_2)$	$(K.E.)_2 = \frac{1}{2}\left[mv_2^2 + I\omega_2^2 + J\dot{\theta}^2\right] \rightarrow J = \int_A r^2 dA$
3	*Rebouncing*	$(P.E.)_3 = (\pi D_{av}^2 / 4.L).g.(h - x_3)$	$(K.E.)_3 = \frac{1}{2}\left[mv_3^2 + I\omega_3^2 + J\dot{\theta}_1^2\right]$
4	*Stationary (over Datum)*	$(P.E.)_4 = 0$	$(K.E.)_4 = \frac{1}{2} I\omega_4^2$

Remarks: [a] *'h'* is measured from the Datum: refer Figure **5**; [b] The distances *{x_1, x_2….}* are measured with respect to the bottom surface of the Reproductive Sack of *Mother* worm robot, *i.e.* distance between 'E' and the in-situ location of the *Daugther* after ejection; [c] (P.E.) for all states is evaluated with respect to the Datum; [d] *'J'* is the resistance of the body of the *Mother* worm robot to being distorted by torsion, as a function of its shape; [*'r'*: torsional radius, *i.e.* linear distance of the central axis of the worm robot w.r.t. the vertical axis; *'A'*: cross-sectional area of the worm robot-body]; e] *'θ'* & *'θ_1'* are the angles of torsion of the body of worm robot, measured from its central axis, at energy-states '2' & '3' respectively.

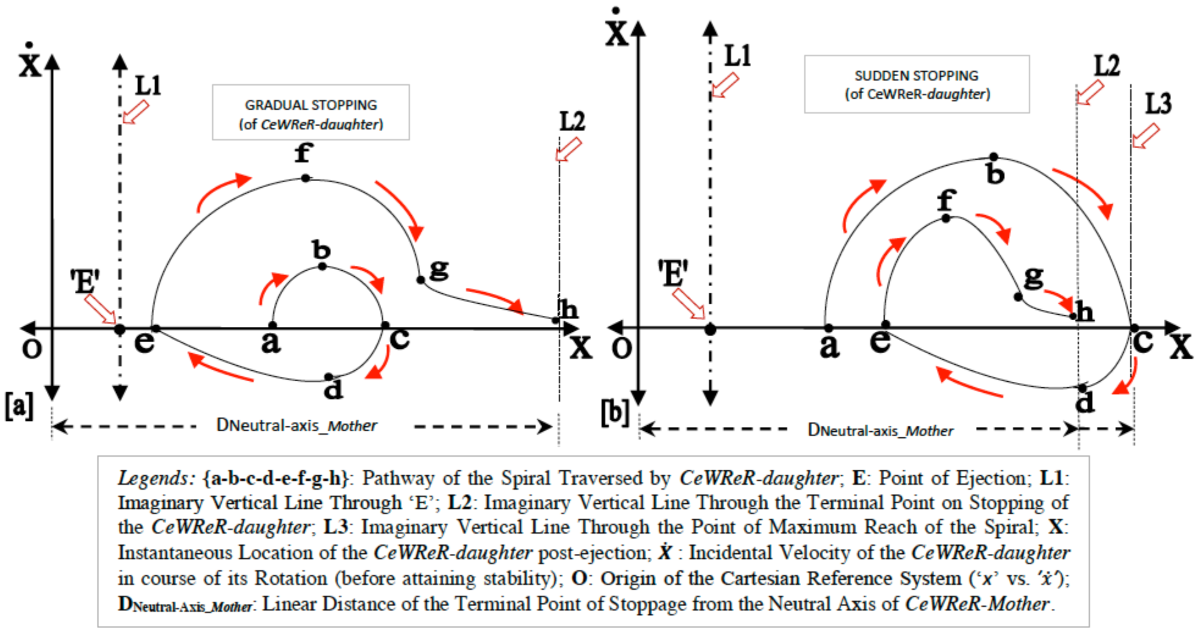


Figure 7: Spiral Paths After Vertical Ejection of *Daughter* Worm Robot: [a] Gradual Stopping; [b] Sudden Stopping.

respect to the axis A-A' or B-B': refer Figure **6a**) and *Case II*: *CeWReR-daughters* are ejected at an angular disposition. It may be noted that under both of the above cases, again two different situations can appear so far as the stopping of the *CeWReR-daughters* over the datum is concerned, viz. i] Gradual Stopping and ii] Sudden Stopping. In fact, the second situation of 'sudden' stopping is quite similar to banging on the datum. Figure **7** graphically illustrates the variation of incidental velocities of the *CeWReR-daughter* with respect to the distance that it has traversed post-ejection under 'case I', branched out for two situations, viz. gradual stopping & sudden stopping. The jerky motion of the '*daughter*' has been represented through spiral, symbolizing change in velocities in two directions (clockwise & counter-clockwise) in course of its fall over the datum. It may be noted that number of spirals can be more than one~ in fact number of spirals will depend on the severity of the initial jerk due to ejection.

We can note the changeover of the dynamics of the *daughter* worm robot(s) after those get ejected out from the *mother* worm robot through the variation of the spiral in Figures **7a** & **7b**. The sprial {a-b-c-d-e-f-g-h} for both the diagrams represents the situation of final stopping of the *CeWReR-daughter(s)* over the horizonatal datum beneath, wherein the physical distances of the via-points (*i.e.* 'a', 'b',…'h') with respect to the point of ejection, 'E' are to be ascertained. Likewise, the instantaneous velocities of the *CeWReR-daughter(s)* (refer *ẋ*) at various intermediate points can be evaluated. While the pair of imaginary lines, viz. 'L1' & 'L2' in figures **7a**,**b** have been drawn to highlight the linear distance of the terminal point of stoppage from the neutral axis of the *CeWReR-mother*, the other line, 'L3' in Figure **7b** symbolizes the maximum distance ('reach') that can be attained by the *daughter* worm robot in course of its spiraling motion. It may be noted that the situation of sudden stopping mostly happens due to 'free fall' of the *CeWReR-daughter(s).* In other words, the velocities at the via-points of the spiral in Figure **7b** will deccelarate fast and the final point of stoppage ('h') will lie well-within the maiden loop of the spiral, *i.e*. {a-b-c}. Thus, the horizontal span between origin 'O' and the via-points 'h' & 'c' are logically the linear distances with respect to *CeWReR-mother*, respectively for the point of stoppage and maximum throughput in course of spiraling. Likewise, linear distances of 'h' & 'c' can also be computed with reference to the point of ejection, *i.e*. with respect to the axis B-B' (refer Figure **6**). It may be observed that no matter how the spiraling originates the cases of gradual stopping versus sudden stopping differ essentially on the arc-length '*gh*' in Figure **7**. In other words, both of these stoppage types are equally likely to occur irrespective of the velocity of the spiral / jerk. Either of these two situations of stoppage can happen with high / low initial velocity of the spiral (*e.g*. arc-segment '*ab*' in Figure **7**).

The variations of incidental velocities of the *CeWReR-daughter(s)* with respect to the traversed distance after ejection under both situations of stopping over datum under 'case II' are illustrated graphically in Figure **8**. While the situation of gradual stoppage of the *CeWReR-daughter(s)* is being pictorially conceived in Figure **8a**, the sudden stopping of the worms over the datum is represented through Figure **8b**. Naturally, *CeWReR-daughter(s)* that are ejected in angular disposition will have more jerk velocities compared to those ejected vertically and such '*daughter(s)*' will need more distance to stop also. We have used the same legends as described in Figure **7**, except the addition of 'θ', which symbolizes the angular disposition of the '*daughter(s)*' upon ejection.

4.4. Basic Design Philosophy of the Reproductive Worm Robot

Honouring the ensemble conceptual framework of the *CeWReR*-system as described in the previous sub-section, we will put forward more substantiative engineering features for both '*daughter(s)*' and '*mother*' *ReproWorm* in this sub-section. The '*daughter(s)*' will be designed in the form of ultra-miniature crawling robots, having tiny legs (2 nos.) and one motor (servo or step-servo) for actuation. As conceived in Figure **5**, *CeWReR-daughters* will be housed inside the '*mother*' in a matrix layout. This layout can be circular or square ~ with pre-fixed dimension / rank of the matrix. The '*mother*' *CeWReR* will be capable of accommodating a total of 'N' no. of '*daughters*' inside the capsule (refer Figures **5** & **6**). The '*mother*' *CeWReR* will have *mouth* & *tail* as per the standard biological configuration of *C.elegans*; but the reproductory cavity of the *CeWReR-mother* will be comparatively larger. It may be noted that the '*daughters*' once released from the body of the '*mother*' will be independent and self-sufficient for any robotic motion, *e.g*. crawling, grazing etc., *i.e*. various locomotions on horizontal plane. The drive-motor of the *CeWReR-daugther* will get energized as soon as it gets stablized over the horizontal datum, post spiraling motion due to ejection. Subsequently, its locomotion will commence over the datum plane ~ however, such locomotions of the '*daughters'* will not be centrally co-ordinated as per the design as of now. If commanded by the *CeWReR-mother*, all or some of the *'daughters'* will go back to the capsule, in case the overall robotic system needs so. The mechanism of 'release' of the '*CeWReR-daughters'* will be sequential, with the help of the *'mother'* (unlike biological *C.elegans*). The

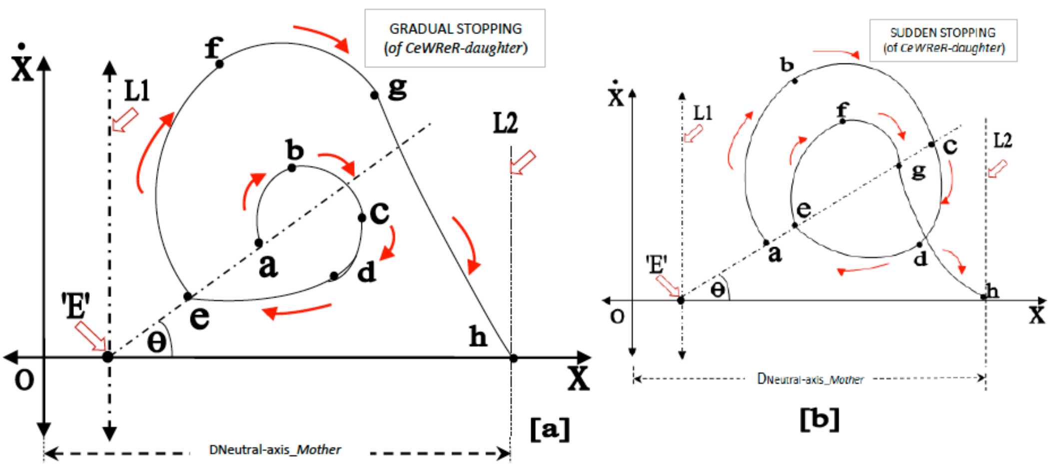


Figure 8: Spiral Paths After Angular Ejection of *Daughter* Worm Robot: [a] Gradual Stopping; [b] Sudden Stopping.

'*daughters'* will be autonomous, via wi-fi connection with the '*mother*'.

It is important to note that while the basic concept of *C.elegans* worm based micro-robot[1] is rooted with the design facets for the locomotion; the auxiliary aspects of such design, *e.g*. reproduction, can be conceived through the design aspects of *CeWReR*, as shown in Figures **5** & **6**. Technology-wise, characteristics of the said *C.elegans* worm based micro-robot ('*CeWMIR*') as '*mother'* must necessarily be fulfilled for the design of *CeWReR* as well, excepting the fact that the prototype *CeWReR* will have two incarnations: '*mother*' & '*daughter*'. Hence, the fundamental design semantics of the *CeWMIR* need to be subsumed in the design of the prototype *CeWReR*.

5. DESIGN FOR ACTUATION OF THE REPRODUCTIVE WORM ROBOT

The biological *C.elegans* performs its locomotion by gradual elongation and contraction of its internal physiological systems. An engineering parallel for this motion can be realized through application of constant pulling force at a pre-assigned location of the body of the *CeWReR*. With the generation of this internal force, *C.elegans* slowly traverses a small linear distance as its maiden run. This process becomes perpetual eventually and the ensemble locomotion gets a finite magnitude. In order to replicate this natural process of locomotion in the robotic system, we need to plan for the following stages of actuation for the *CeWReR-mother*, viz.: *Stage I*: Initiation of rolling; *Stage II*: Initiation of micro-translation; *Stage III*: Application of external forcing and *Stage IV*: Incipient locomotion. However, this actuation protocol of *CeWReR-mother* will not be applicable for the '*daughter(s)*', because the locomotion of the *CeWReR-daughter* is not self-generated. The *CeWReR-daughter(s)* will be pushed through a novel Pusher Mechanism (PM) that will produce jerks / vibration to the Reproductive Sack (RS). With this backdrop, we will now detail out the variations and subtle features of the design for actuation for the '*mother*' and '*daughter*' *CeWReR* separately in the following sub-sections.

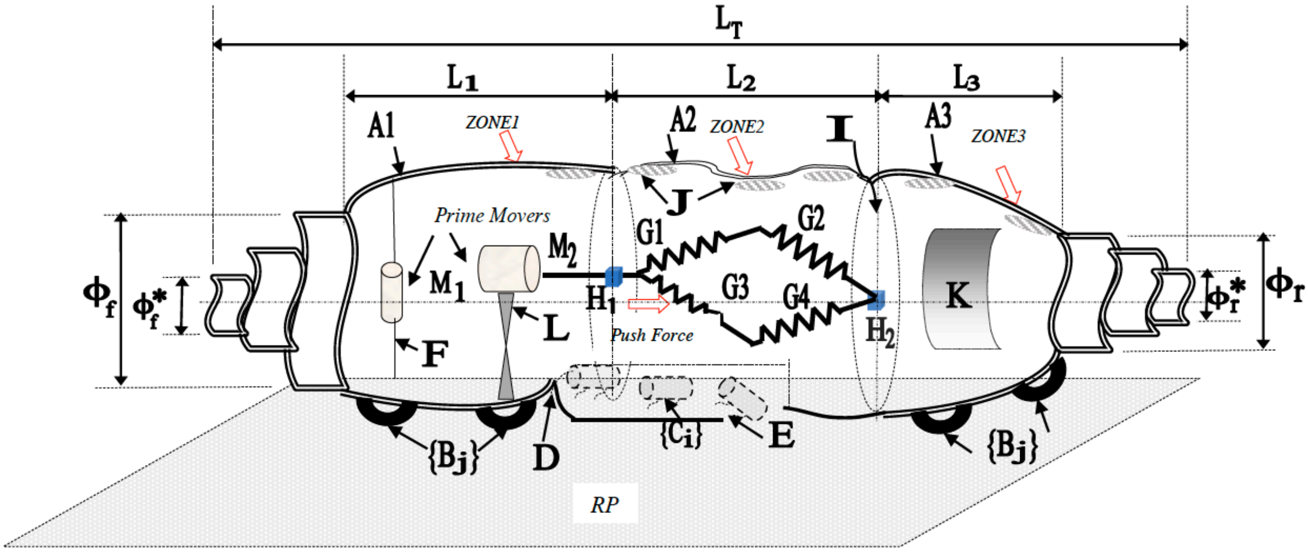
5.1. Design for Actuation of the 'Mother' Worm Robot

In order to facilitate the four stages of actuation for the '*mother*' worm robot, as stated above, conceptually, the ensemble torpedo-like body of the *CeWReR-mother* has been divided into three 'zones', out of which two end-zones will be 'active' while the middle zone is 'passive'. The two active zones will be separated by a mechanical spring. These three zones will be dimensionally dissimilar and those will represent the front, middle & back side of the worm robot respectively. Placed in-between, the spring will have rigid connection with these two zones.

We shall dwell on two different design-schemes for *CeWReR-mother*, primarily on the basis of the capacity to hold '*daughters*' till the time-instant of ejection, *i.e*. size of the 'RS'. While the first design-scheme will be apt for holding upto 3 '*daughters*', the second design is conceptualized with a bigger size so that it can house 4 '*daughters*' at a time. For both designs, there will be a slot in the middle zone, wherefrom *'daughters'* will drop out from the 'RS' of the '*mother*' on the horizontal plane below. Each of the front & rear zones of the *CeWReR-mother* will have two pairs of micro-wheels (*i.e*. total of 8 nos.) for easy locomotion, namely, rotation as well as translation over the horizontal surface. Figure **9a** shows the ensemble exterior layout of the *CeWReR-mother* with demarcation of the 'zones', led by the motion analogy for its biological counterpart. As can be observed in Figure **9a**, we have conceptualized two 'sources' of motion-generators, *i.e*. prime-movers for: i] *perpetual rotation* of the worm robot and ii] *translatory motion & pushing force function* for the internal spring. It may be noted that the pushing force for the spring indirectly helps the worm robot to move forward in a slow pace. In a way, our designs will help realizing both rotation as well as translation (limping) of the *CeWReR-mother* over a finite time-period. While the fundamentals of the motion-generators will remain unchanged, design-schemes for the *CeWReR-mother* will be lengthier in comparison to *CeWMIR*, due to the incorporation of the 'RS' & allied ejection mechanism of the *'daughters'*. Figure **9b** illustrates the engineering details of mounting the micro-wheels with the body of the *CeWReR*. We have conceptualized a curvy exterior for the prototype *CeWReR*, in-line with biological *C.elegans* ~ the said exterior is divided into three portions (refer A1, A2 & A3 of Figure **9a**). The other aesthetically significant attribute that has been added in the design is the protruded tapered portions at the front & back side of the worm robot, which corresponds to two ssets of diameters at the front & back end of the robot, namely, [ϕ_f & ϕ_f^*] and [ϕ_r & ϕ_r^*].

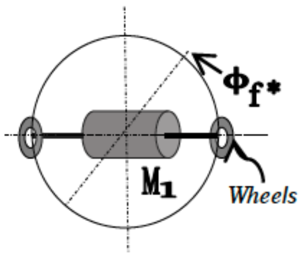
The basic triad responsible for the generation & subsequent translation of the motion for *CeWReR-mother* is {M_1, M_2, G}. While the prime mover 'M_1' is designed for the production of rotational motion the other one, 'M_2' is used for the generation of push force through the attached spring, 'G' and the couplers {H_1, H_2}. It may be noted that 'M_1' is selected as bi-directional type so that the rotary motion can be transferred easily to the pair of wheels at the front-end

[1] *C.elegans* Worm based Miniature Intelligent Robot (*CeWMIR*): another indigenous design of worm robot, made by first author.



Legends: **{A1, A2, A3}:** '*Mouth*', '*Body*' & '*Tail*' of the Worm Robot (*CeWReR*); **{Bj}:** Micro-wheels; **{Ci}:** '*Daughter*' worm robots; **D**: Reproductive Sack of the '*Mother*' Worm Robot; **E**: Zone of Ejection of the '*Daughters*'; **F**: Axles for the Wheels; **{G1, G2, G3, G4}**: Springs; **{H1, H2}:** Couplers for Prime Mover & Support Frame; **I**: Support Frame of 'A3'; **J**: Tactile Sensors; **K**: Sensor Processing Unit; **L:** Mounting Fixture; **{M1, M2}:** Prime Movers (Servomotors) for the Motions of Wheels & Push Force; **RP**: Reference Plane (Datum)

Figure 9a: Design for Actuation of the 'Mother' Worm Robot (*CeWReR-mother*).



Design Data: L_1: 40 mm; L_2: 110 mm.; L_3: 20 mm; L_T:170 mm; ϕ_f:30 mm.; ϕ_r: 20 mm.
[Drawing is not in scale]

Figure 9b: Design of the Micro-wheels and Fittment with the 'Mother' Worm Robot (*CeWReR-mother*).

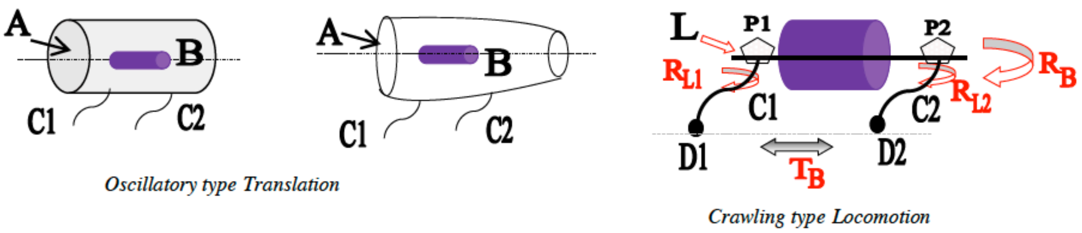
of the *CeWReR*-body via the axles 'F'. Although the frontal pair of wheels are positive powered directly from 'M_1', the rest 3 pairs of wheels (1 pair in the frontal side & the other 2 pairs at the tail-end) are essentially non-powered type, *i.e.* castors. Nonetheless, the 2 pairs of wheels at the tail-end will have sufficiet extra translatory motion by virtue of the spring force, generated at *zone 2*. We may note that only one no. wheel is shown in Figure **9a** out of each pair, in order to have better clarity on the actuation mechanism. Figure **9b** illustrates the physical assembly of the driving wheels with 'M_1' (on both sides of *zone 1*). The diameter of the particular cross-section in *zone 1* where the prime-mover 'M_1' is attached is represented by 'ϕ_{f^*}', where $\phi_f < \phi_{f^*}$. As a theoretical extrapolation of this paradigm, positive motions for the rear-wheels at *zone 3* would have culminated in the similar scenario of wheel assembly with $\phi_r < \phi_{r^*}$. Alongwith the motion signature, it is wiser to look at the ensemble dimensions of the prototype *CeWReR-mother* ~ such as: total length 'L_T' (~ 250 mm.), frontal diameter 'ϕ_f' (30 mm.) and rear diameter 'ϕ_r' (20 mm.). The cross-sectional diameters of '*zone 2*' can be deduced from geometry, considering uniform tapering of the *zone 1* & *zone 3*. There will be a slot in '*zone 2*' (refer 'E'), wherefrom '*daughters*' will drop out from the '*mother*' on the horizontal datum ('RP'). It is needless to say that the capacity of *CeWReR-mother* will be defined in terms of 'carrying volume' for the '*daughters*'.

5.2. Design for Actuation of the 'Daughter' Worm Robot

Daughter CeWReRs will be of identical design as that of '*mother*', except external dimensions. Hence, we will consider similar torpedo-like ensemble for the '*daughters*', with same equal end-diameters and slightly buldged out central zone. However, unlike '*mother*', the central zone of the *daughter CeWReRs* will not have any extended profile; rather it will be designed at sufficiency for accommodating the miniature drive-motor inside. Besides, '*daughters*' will be actuated with the help of a pair of tiny legs or modified micro-wheels. The characteristic design features of the '*daughters*' are: a] ensembe length: 20

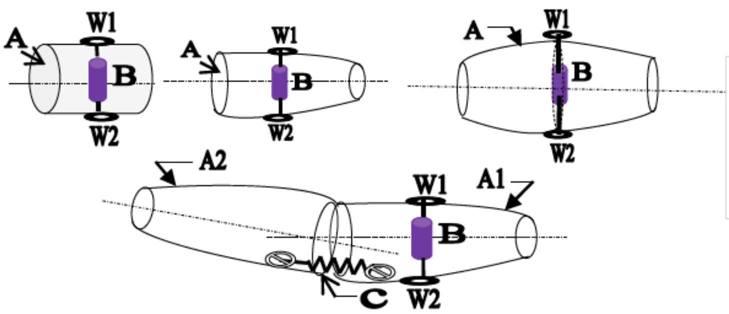
mm. & end-diameters: 3 mm. & b] length of legs / diameter of wheels: 2 mm. It may be noted that only one micro-motor will be used for actuation as well as locomotion of the '*daughter*'. Unlike '*mother*', no spring-loaded internal mechanism will be used in case of '*daughters*'. The exterior surface of the prototype '*daughters*' will be slightly bi-tapered with identical angle of taper at both ends, *i.e.* '*Head / Mouth'* & '*Tail*'. Thus, the ensemble body of the '*daughter*' is divided into two zones only~ this feature is a bit different from that of the '*mother*'. However, we will also adopt right-circular type cylindrical ensemble for the body of the '*daughters*' due to ease of manufacturing, especially for the locomotion with legs. The crucialmost aspect for the hardware prototyping of the '*daughter*' is the fittment of the tiny servomotor inside the hollow hub. We have designed only two legs / wheels for its locomotion~ and those will be placed centrally with respect to the motor. Figure **10** shows the design for actuation of a representative '*daughter*' worm robot with tiny legs for two types of designs of the body.

As delineated pictorially in Figure **10** above, we have conceptualized two different configurations for the 'body'of the prototype '*daughter*' *CeWReR*, namely: cylindrical shape and uni-tapered torpedo-like shape. The actuating motor ('B') will be housed inside the 'body', while the pair of miniature legs (C1, C2} will be projected out of the body. The design of the legs is unique, in a sense that these will have curved ensemble with small spherical end-pieces at each leg [refer {D1, D2}]. These spherical end-pieces are designed in order to have smooth contact of the legs with the datum in course of translatory motion over horizontal plane. It is important to note that the final translatory motion of the '*daughter*' worm robot will be oscillatory, as the source-motion is rotary (via motor 'B') while the transferred motion is semi-linerar (over the datum). Hence, by virtue of non-analogous motion, the resultant motion ought to be oscillatory. The primary rotation motion of the actuator ('R_B') is generated inside the central transmission shaft ('L'), which is responsible for its onward transmission to the pair of legs. The rotational motions in the legs, viz. {R_{L1}, R_{L2}} get realized through a novel mechanism, having a pentagon-shaped retainer plate at each end of 'L'. These retainer plates [refer {P1, P2}] intake the rotary motion of the central shaft and output the same motion to the legs in an intermittent manner. The retainer plate-induced transferrence of motion has similarity to the traditional cam-follower mechanism of motion transmission. Since the retainer plates transmit rotary motion to the legs in intermittent fashion, the induced rotary motion of the legs will have wobbling in real-time. Thus, the final augmented motion of the '*daughter*' *CeWReR* will be crawling type locomotion ('T_B') over the datum, signaling the intermittence wobbling of the ensemble mechanism. In contrast to the ideation of the locomotion with tiny legs, the design for actuation of a representative '*daughter*' worm robot with miniature wheels is illusatrated in Figure **11**, using three different forms of the exterior body.



Legends: **A**: Body of the '*Daughter*' Worm Robot; **B**: Actuating Servo-Motor; **{C1, C2}**: Assembly of the Miniature Legs; **{D1, D2}**: Spherical End-pieces of the Legs; **L**: Central Transmission Shaft; **{P1, P2}**: Pentagonal Retainer Plate; **R_B**: Primary Rotational Motion of the Central Shaft; **{R_{L1}, R_{L2}}**: Rotational Motion of the Legs; **T_B**: Oscillatory type Translation

Figure 10: Two Representative Designs for Actuation of '*Daughter*' Worm Robot with Tiny Legs.



Legends: **A**: Body of the '*Daughter*' Worm Robot; **B**: Actuating Servo-Motor; **{A1, A2}**: Seprated Head & Tail Units of the Body (in case of Bi-lobed '*Daughter*'); **C**: Spring for Postural Adjustiments; **{W1, W2}**: Miniature Wheels

Figure 11: Four Representative Designs for Actuation of '*Daughter*' Worm Robot with Miniature Wheels.

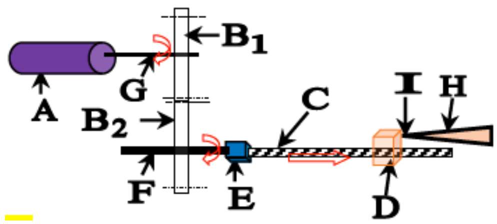
The design of the *CeWReR-daughter* has been conceptualized for nearly smooth rolling-type locomotion with the help of a pair of miniature wheels, as detailed schematically in Figure **11**. For ease of transmission of the rotary motion of the actuator ('B'), both the wheels, (W1, W2) have been attached to the double-ended motor-shaft. The wheel assembly and associated transmission mechanism is universal for all three variants of the 'body', nmaely, cylindrical, uni-tapered, bi-tapered (torpedo-like). The design slightly differs in case of bi-lobed body that has got distinct separate units of 'head' & 'tail'. In this case, the motor-wheel conjugate assembly is placed inside the 'head' unit ('A1') of the worm robot. The generated rotary motion gets transmitted to the 'tail' unit ('A2') through a compressible sprimg ('C'). Naturally, the ensemble locomotion of this type of '*daughter*' robot with bi-lobed body will be jerky, as the trailing unit will have tendency of tracing a curvilinear path intermittently.

5.3. Design for Actuation of the Pusher Mechanism:

The '*daughters*' will be pushed through a novel 'Pusher Mechanism' (PM) that will produce jerks / vibration to the 'Reproductive Sack' (RS). Hence, '*daughters*' will move forward one-by-one in a sequential manner inside RS and eventually fall-off from the 'Ejection Zone' (refer 'E' in Figure **9a**). This 'Ejection Zone' is nothing but a semi-wide 'gap' in the body of RS, mesuring around 10 mm. The activation of 'PM' will be governed by the prime-mover, 'M_2' (refer Figure **9a**), alongwith a spur gear-train. It is needless to state that the entire sub-assembly of 'PM' will be concealed inside the body of the *CeWReR-mother*, just outside the physical disposition of 'RS'. Figure **12** schematically shows the mechanical sub-assembly of 'PM' with a pictorial explanation about its actuation.

The actuation of 'PM' takes place primarily through the servomotor (prime mover) assembly, 'A'. The rotary motion from 'A' gets ttransmitted via 'G' to the spur gear train, {B_1, B_2}. The final rotational motion gets transmited to a recirculating ball screw-nut assembly (refer 'C' & 'D' in Figure **12**), via 'F' & 'E'. The design & selection of 'C' will be made in such a way so that its linear traverse can cover up the desired task of pushing all the '*daughters*' through the exit chute. However, the very phenomena of 'pushing' the '*daughters*' inside the Reproductive Sack will be carried out by a specially-designed wedge, 'H'. This wedge will have rigid connection with Nut, 'D' in order to ensure minimum loss of energy during pushing operation. Once the ball screw-nut assembly sets in linear translational motion the wedge 'H' comes into action and push becomes perpetual. Once the first 'daughter' gets the requisite push it swivels & gets ejected through the exit chute. By that time, the ball-screw-nut assembly advances to a pre-assigned distance and the wedge starts pushing the second '*daughter*'till it gets ejected. This process continues till all the '*daughters*' in the RS are exhausted. The assemblage of the pushing mechanism with the reproductive sack of the *CeWReR-mother* is depicted pictorially in Figure **13**.

As illustrated in Figure **13**, the primary push force generated out of the pushing mechanism gets transferred to the leftmost '*daughter'* in the RS through the contact of the wedge. This push force should be



Legends: **A**: Servomotor (Prime Mover); **{B₁, B₂}**: Spur Gear Train; **C**: Recirculating Ball Screw; **D**: Nut (for ball screw); **E**: Coupler; **F**: Ball Screw Connecting Shaft; **G**: Motor Shaft; **H**: Pushing Wedge; **I**: Nut-Wedge Rivet

Figure 12: Schematic Design of the Pushing Mechanism of the *ReproWorm*.

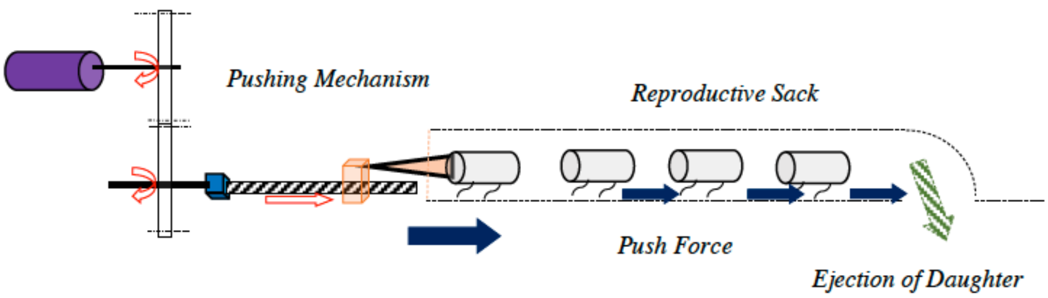


Figure 13: Pictorial Representation of the Pushing Mechanism & Reproductive Sack Assemblage of *ReproWorm.*

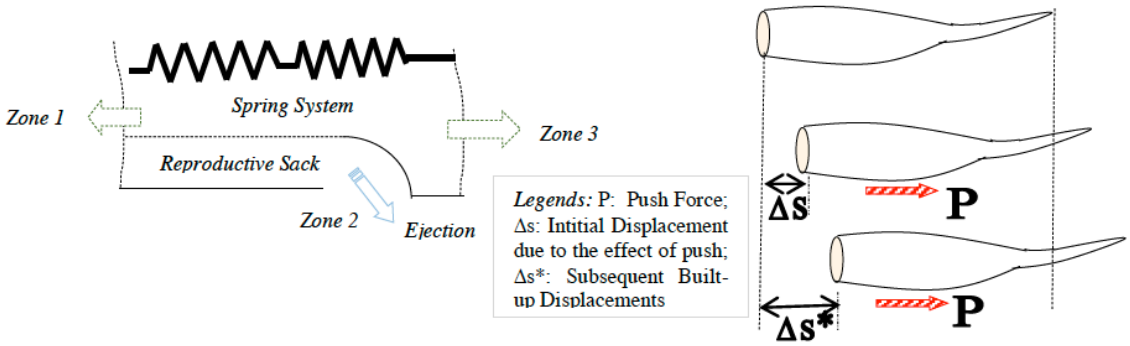


Figure 14: Schematics of the Positional Syntax of the Spring inside Mother Worm its Effect in Curvy Locomotion.

sufficient enough to move the next daugher little forward and so on. Finally the said primary push force will be successful in toppling the rightmost '*daughter*' through the ejection chute. It may be mentioned here that the spring-contact between *zone1* & *zone3* of the *CeWReR-mother* (refer Figure **9a**) is also crucial in maintaining the overall translatory motion of the '*mother*' worm robot, post ejection of the '*daughter(s)*'. In fact, by virtue of the spring system, the *CeWReR-mother* is able to keep its body in transverse motion over the datum plane~ much alike the locomotion of the biological *C.elegans*. Figure **14** shows the positional effect of the spring system inside the body of the *CeWReR-mother* and the overall curvy locomotion of the same.

The crux of the planar locomotion of the *CeWReR-Mother* is the activation of the internal spring system (between *zone1* & *zone2* of the body). This activation, by virtue of the application of the push force, 'P' becomes instrumental is creating the maiden displacement of the worm (Δs) over the datum. The effect of this push force continues to increase in a slow pace as time progresses, which finally results in built-in displacements (Δs*). These add-on displacements are responsible for the locomotion of the worm robot.

5.4. Final Designs for Prototyping of the Reproductive Worm Robot

Two prototype designs for the *ReproWorm* have been finalized on the basis of the capacity for accommodating '*daughters*' inside the reproductive sack of the '*mother*'. The design capacity of *CeWReR-mother* will be defined in terms of carrying volume for the '*daughter*' *CeWReRs*. The first prototype of the *CeWReR-mother* is designed for holding 3 '*daughters*' and the second one is designed for carrying 4 '*daughters*'. It may be noted that further increase in the said carrying capacity of the *CeWReR-mother* will be infeasible practically because of comparatively large volume. Also, the ensemble length of the any one prototype *ReproWorm* will be more than the length of the prototype *CeWMIR*. Figure **15** illustrates the designed disposition of the first prototype *CeWReR*, accommodating three '*daughters*'.

The exterior of the first prototype *CeWReR* has been designed with a bi-tapered hollow cylindrical

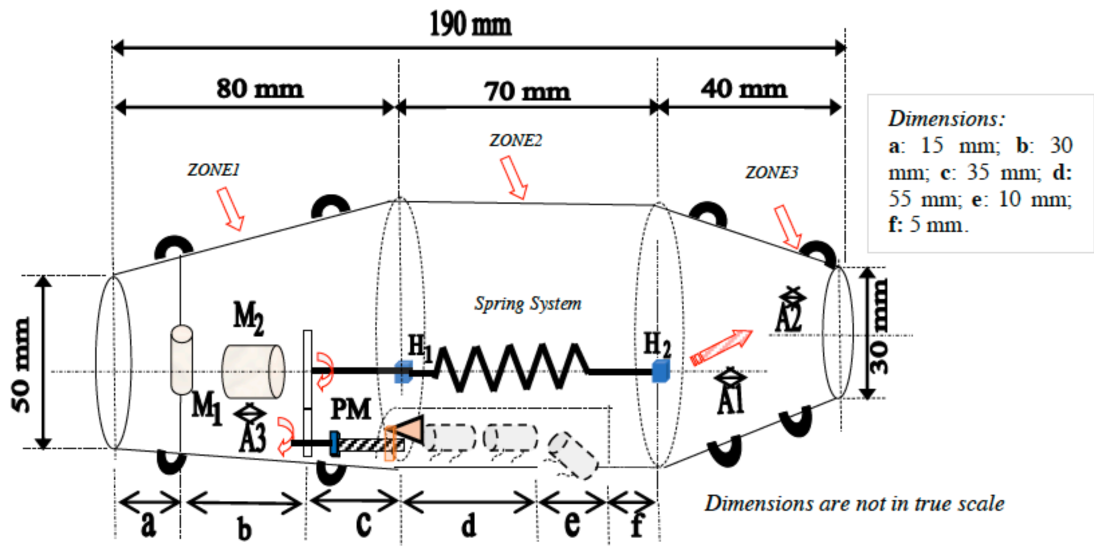


Figure 15: Designed Layout of the Prototype Reproductive Worm Robot Carrying Three '*Daughters*'.

disposition with an ensemble length of 190 mm.; while dissimilar 'head' & 'tail' diameters are of 50 mm & 30 mm. respectively. The zone-wise lengths have been conceived with a view towards accommodating internal components & sub-assemblies, viz. two nos. servomotors (M1 & M2) and Pusher Mechanism (*PM*), besides '*RS*'. Functionally, *zone1* & *zone2* are very significant as these two zones contain all essential toolings of the robotic system. In comparision, *zone3* is basically a support sub-system for the locomotion of the *CeWReR-mother.*With this backdrop, lengths of the first two zones are optimized (80 mm. & 70 mm. respectively) with respect to the segments, namely 'a', 'b' & 'c' (for *zone1*) and 'd', 'e' & 'f' (for *zone2*). The nucleus of the design is rooted in the disposition of the three imaginary central axes, viz. A1, A2 & A3. It may be noted that A1 is responsible for synchronizing the dispositions of: i] {M1,M2}; ii] driving gear of '*PM'* and iii] end-couplers (H_1 , H_2) of the spring system. On the other hand, A3 is crucial is transferring the rotary motion of the driven gear of '*PM*' through the lead screw-nut-wedge assembly for generating the requistite push force to dislodge the first '*daughter*' and so on. In contrast to the functioning of A1 & A3, the central axis A2 is dedicated towards transfer of the spring-generated push-force inside *zone3* so that the '*tail*' emd of the worm robot gets adequate boost up for the planar locomotion with the help of 4 pairs of miniature wheels or legs. However, relative positioning of these three imaginary axes may be altered slightly considering ease of manufacturing. We may also observe that the dimensioned layout of the '*RS'* has been made in such a way that two '*daughters*' can always remain inside comfortably (refer dimension of 'd'), while the third one will be in the verge of ejection through the duct (refer dimension of 'e'). The other important design paradigm that needs clarification is the optimal span of *zone2*, precisely the ensemble length of the spring system therein. Since nearly the entire volume of '*RS*' has been accomodated in *zone2*, there is no further scope of increment of the size of '*RS*' due to the limitation of the strength of the spring system. In that respect, the length of *zone2*, *i.e*. 70 mm should be treated as the upper threshold of the design for manufacturing. It may be noted that an equivalent spring system has been used between H_1 & H_2 to simplify the drawing. This equivalent spring is composed from four individual springs (vide G1, G2, G3 & G4), a s shown in Figure **9a**. We have also simplified the curvilinear exterior as well as tapered lobes at the front & back-end for clarity of the dimensions, in contrast to the artist's view of the scheamtic, showb in Figure **9a**.

The designed layout of the second prototype *CeWReR*, carrying four '*daughters*' is shown in Figure **16**. The most salient feature of this design is the altered positioning of the '*RS*'~ which is now in *zone1*. Accordingly, the span of *zone2* is reduced substantially as it houses only the ejection chute of the '*RS*' besides a spring system of shorter length. It may be noted that flap-type or hinge-type cover will be used in both prototypes for easy fittment as well as assembly / disassembly of the motors. We have retained here the ideation of curvilinear exterior as well as tapered front-back features of the prototype CeWReR, as depicted in Figure **9a**. Accordingly, the ensemble length of the reproductive worm robot has been arrived at.

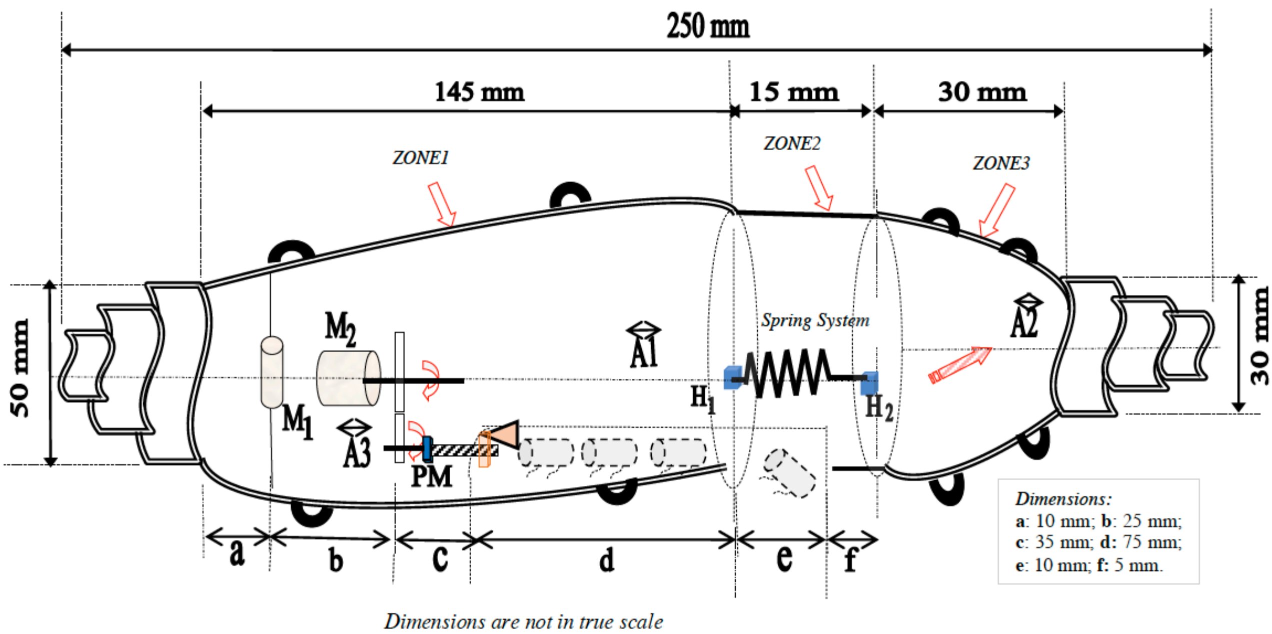


Figure 16: Designed Layout of the Prototype Reproductive Worm Robot Carrying Four '*Daughters*'.

Although the above-stated designs are optimal in all respect for practcal applications such as rescue operations and agricultuiral fields, it is possible to build bigger-sized *CeWReR* with carrying capacity of 5 or 6 *daughters*, for the sake of experimental investigation and synthesis at the laboratory.

We shall now look into the design for manufacturing of the *CeWReR-daughter*, for which schenatics of Figures **10** & **11** may be referred. We have detailed out the said designs, namely four with micro-wheels and two with tiny legs, mainly with respect to the end- as well as interim-diameters, overall length, wheel diameter and leg-length. Figure **17** illustrates the dimensioned outlay of these six variants of *CeWReR-daughters*.

Dimension-wise, one of the trickiest components is the micro-wheel, because of its tiny diameter (3 mm.). The other subtle sub-assembly will be that of the servomotor, inside the hollow housing. Although fittment of the tiny motor is somewhat managable for '*daughters*' with cylindrical-shaped housing (refer design [a] & [e]), it is challenging in case of tapered housing (refer design [b], [d] & [f]). In contrast to these, design [c] has some recess for the placement of the motor, as the housing is bi-lobed with enlarged diameter at the mid-section. The most complicated design of these six variants is design [d], wherein we have used two tapered housing, connected by an adjustible spring. The right-hand-side lobe will be the driver with servomotor fitted inside and the other lobe will be driven by the same. Fittment of tiny legs is another challenging aspect, as it is illustrated (refer design[e] & [f]). It may be noted while all of these six design-variants are feasible so far as hardware prototyping is concerned; we have earmarked design [e] for its compactness and ease of manufacturing for the prototype reproductive worm robot (refer Figures **15** & **16**).

We may note that there are few *open* research issues so far as the design for manufacturing is concerned for either of the *CeWReR* prototypes~ be it '*mother*' or '*daughter*'. There are six crucial open issues in the prototype design of the *CeWReR-mother*, viz.: i] *Time* of reproduction; ii] *Frequency* of reproduction; iii] *Direction* of the ejected / falling '*daughters*'; iv] *Fittment* of the prime-movers; v] *Assembly* of the Reproductive Sack & vi] *Impedance Control* over the reproduction process. Likewise, we can identify five open issues in the prototype design of the *CeWReR-daughter*, viz. i] *Direction* of ejection from '*mother*'; ii] *Time* of ejection; iii] *Frequency* or *Interval* between two succeding ejections; iv] *Impedance Control* over the ejection process & v] *Locomotion* of the '*daughter*', just immediately after the ejection. It may be noted that a few of the above issues have commonality; in other words, concepts are similar for both '*mother*' as well as '*daughter*' *CeWReR*. For example, the concept of '*reporoduction*' (in case of '*mother*') and '*ejection*' (in case of '*daughter*') have equivalent technical parlances so far as time, frequemcy or impedance control is

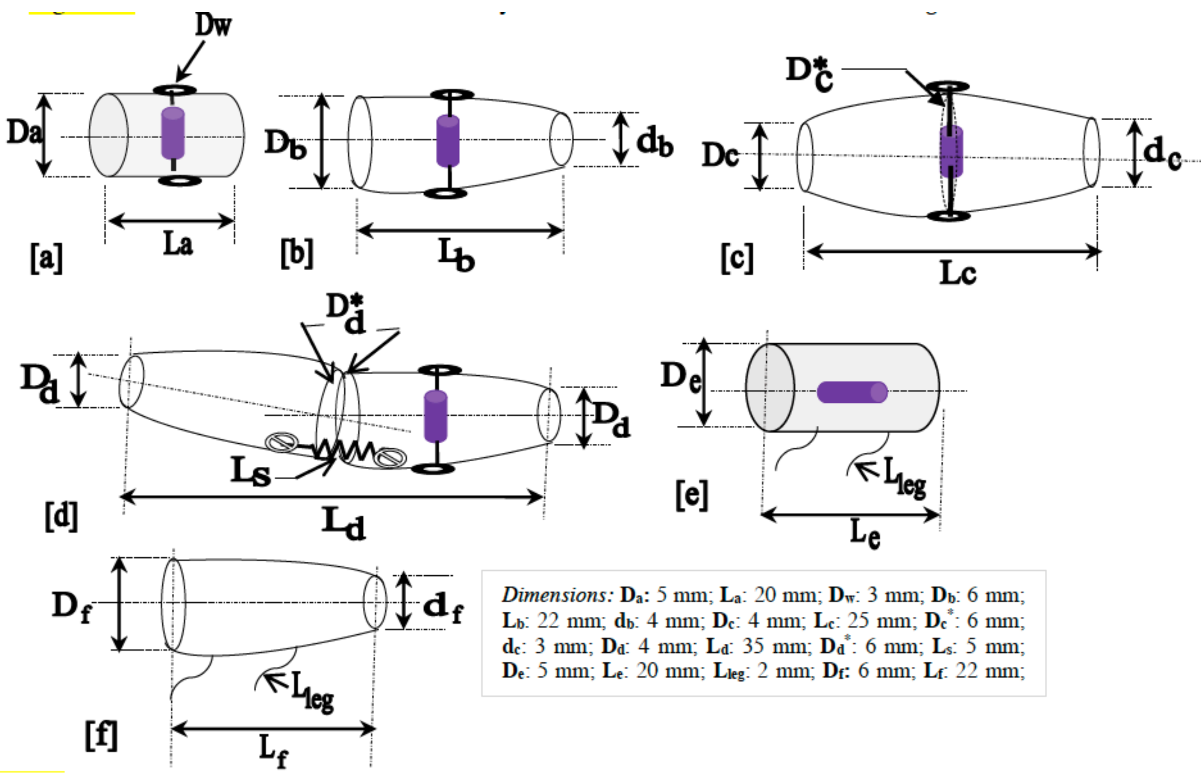


Figure 17: Dimensioned Outlay of the Six Variants of *Daughters* of the Prototype Reproductive Worm Robot.

concerned. It is also true that the open resesarch issues for both *CeWReR-mother* & '*daughter*' are quite similar to that of the biological process of reproduction in *C.elegans* worm. The only difference being the realization semantics~ in case of *CeWReR* all those metrics are evaluated in terms of technical parameters.

6. SYNTHESIS AND EXPERIMENTAL VERIFICATION OF THE DESIGN

The designs of the *ReproWorm,* as detailed in the previous sections, were synthesized further for the experimental verification of the prototype. In this context, we selected the design of the *CeWReR-daughter* to begin with, because of its relative ease in manufacturing. However, the hardware manifestation of the '*daughter*' worm was conceived with leg-type deisgn (refer Figure **17e**), which may be entrusted to be a relatively complex in comparision to wheel-type incarnations. The fabrication of the representative '*daughter*' worm robot was achieved through 3D printing technology, wherein we have used all non-metallic semi-compliant components (except the servomotor assembly) to reduce the tare-weight. These components do follow three fundamental attributes of Physics, so far as the final locomotion of the '*daughter*' is concerned. These attributes are: a] Expansion of cross-sectional area; b] Shear & c] Bending. Figure **18** pictorially illustrates these three attributes.

Table **3** presents the technical specifications of the prototype *CeWReR-daughter* as achieved post-manufacturing, alongwith its working parameters (refer sl. no. 5 to 7).

Table 3: Technical Specifications and Working Parameters of the Prototype *CeWReR-daughter*

Sl. No.	Design Parameter	Numnerical Value
1.	Length	87.05 mm.
2.	Width / Diameter	46.1 mm.
3.	Height	54 mm.
4.	Weight	81.9 gm.
5.	Tare Weight	82 gm.
6.	Minimum Diameter of the *Reproductive Sack*	55 mm.
7.	Average Speed of Locomotion	12.46 mm/sec.
8.	Average Angular Deflection (during locomotion)	31.6^0

The prototype *CeWReR-daughter* was tested for its actuation by the bi-directional shaft servomotor and locomotion over horizontal datum by invoking a DC power supply source of 9V. Figure **19** shows the photographic views of the prototype *CeWReR-daughter*, both external as well as internal.

Interestingly, we could manufacture three variants of the miniature legs for the prototype *CeWReR-daughter*, having varying thickness. While these variants are marginally differing length-wise, those have substantial effect when maximum equivalent stress was computed. As '*daughters*' need to sustain not only the free-fall due to ejection from the RS but also the locomotion over the datum, it should have comparatively less stress, else there will be a chance of breakage of the leg(s). The three variants of

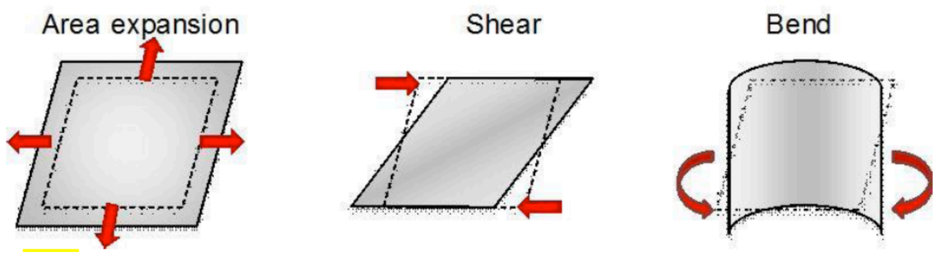


Figure 18: Three Fundamental Physics-specific Attributes for the Hardware Manifestation of *CeWReR-Daugther.*

Figure 19: Photographic Views of the Prototype *CeWReR-Daughter.*

the manufactured legs are of length 3 mm, 3.1 mm & 3.2 mm. respectively ~ maximum values of the corresponding equivalent stress are 6.08 MPa, 5.62 MPa & 4.81 MPa under normal working condition.

The prime objective of experimenting with the prototype *CeWReR-daughter* was to check how far it can traverse in the horizontal plane without any pause, under the designed value of angular speed. This testing was crucial, as we needed to judge a-priori about the potential stability of the '*daughter(s)*' post-ejection as well as independent locomotion of those. Table **4** presents the experimental data for the distance traversed by the prototype '*daughter*' through activation of a 9V battey for 10 seconds, at various uncorrelated test-runs. Two allied parameters, namely average speed of locomotion and angular deflection /tilt of the system (due to the actuation of the tiny legs) were also noted during the trials.

Table 4: Particulars of Locomotion of the Prototype *CeWReR-daughter*

Test-Run	Distance Traversed (mm.)	Average Speed (mm/sec.)	Angular Deflection (degree)
1.	143	14.3	23
2.	142	14.2	28
3.	135	13.5	39
4.	105	10.5	35
5.	98	9.8	33

The paradigms of planar locomotion of the *CeWReR-daughter*, as reported in Table **4**, were experimented for different terrains, including few non-coherent work-zones. Figure **20a** shows the photographic view of the slow locomotion of the '*daughter*' using legs in order to enter inside a wooden chute. Post-entry, various stages of movement of the same through the chute having minimum clearance are

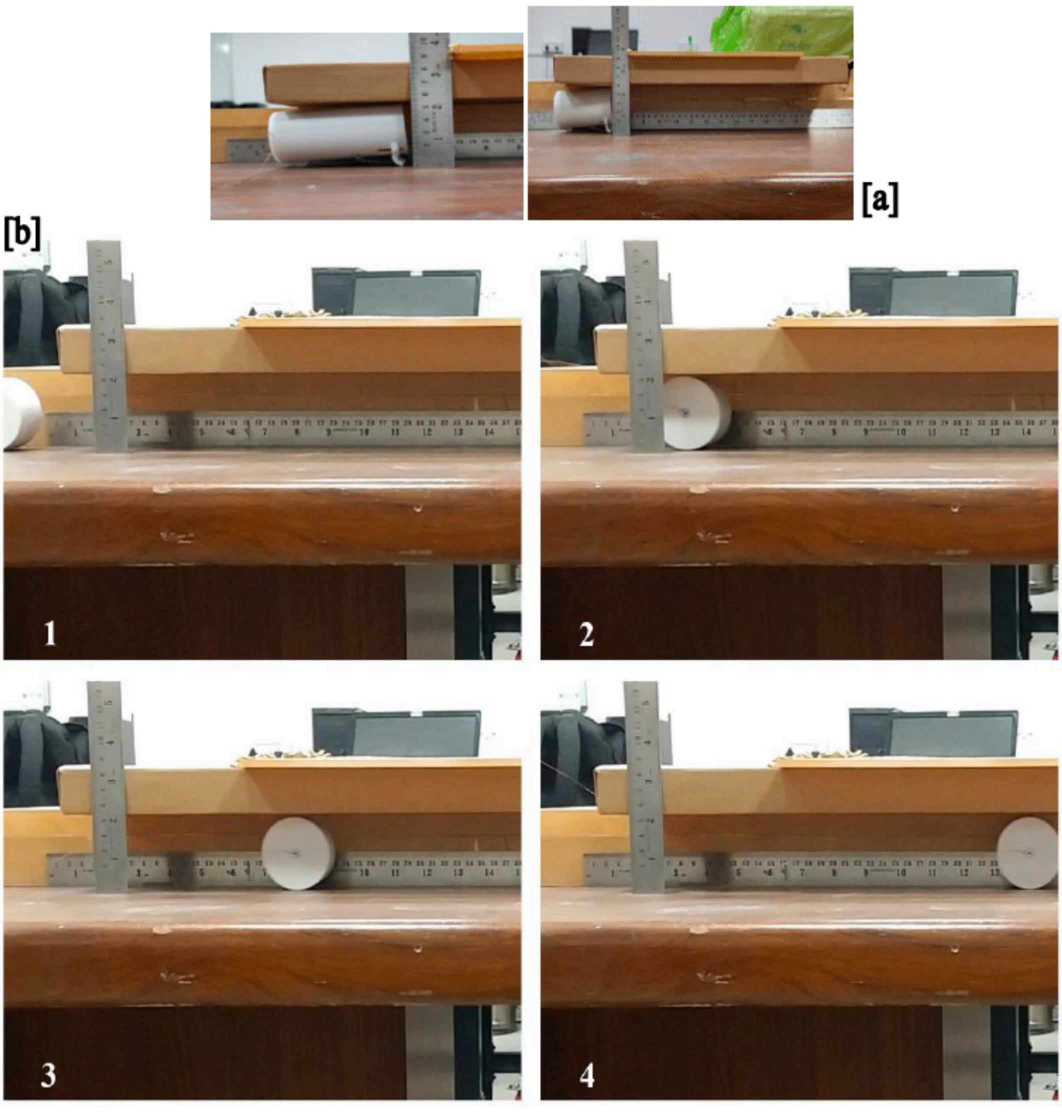


Figure 20: Experimental Run of the Prototype *CeWReR-Daughter* through a Chute: [a] Entry; [b] Interim Stages.

depicted in Figure **20b** (sequentially from entry to exit, viz. ‘1’ to ‘4’).

The experimental paradigms for the prototype *CeWReR-daughter* were found to be satisfactory in all respect, barring sizing issue. Attempts are currently underway to fabricate miniature version of the said ‘*daughter*’ that will be commenssurate with the ensemble design of the *ReproWorm*. The prototyping of the *CeWReR-mother* will commense soon after the phase II trials of the ‘*daughter*’.

7. CONCLUSIONS

Synergy between biology and technology is the current trend of research in the domain of prototyping miniature-scale robotics. Although paradigms of bionic robots are in the fray for quite some time, the concept of reproductive robot is not heard hitherto to the best of our knowledge. A successful culmination of the design for manufacturing of such a reproductive worm-type robot followed by its prototyping will usher in a novel frontier not only in the academic research but also in several application manifolds. It may be appreciated that we will need reproductive worm robots in such domains where moderately significant quantities of ‘*daughters*’ are required to work. Two such prominent fields of potential applications of reproductive worm robots are rescue robotics and agricultural robotics. Both of these two arenas require coherent & co-ordinated operation of ‘*mother-daugther*’ worm robots in real-time. Nonetheless, the crux of such deployment scenarios is essentially linked up to the in-situ requirement of multiple locomotion-enabled robots, generated out of ‘*reproduction*’ from the ‘*mother*’ worm robot. With this backdrop, our proposed designs of the reproductive worm robots, inherited from the biological worm *C.elegans*, can be entrusted to fulfil application-specific requirements towards accomplishing a co-ordinated task in the near future.

CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

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