Zombie Swarms: An Investigation on the Behaviour of Your Undead Relatives

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Abstract. While zombies have been studied in a certain detail *in vivo*[1], the attention has been mostly focused on small-scale experiences, typically on case studies unexplicabily concentrating on just a hero and a few dozen zombies. Only recently a new, fruitful area of research on the behaviour of *masses* of zombies has been investigated.

In this paper, we focus on modeling the behaviour of swarms of zombies, according to the most recent theories of their cognitive, sensorial and motion capabilities. In so doing, we also formulate recommendation on how the hero might survive while putting the minimum effort needed to succeed, thus helping keeping the sufficient amount of suspense in future research scripts.

1 Introduction

Since the seminal study of Romero et al. [1] and their follow-up work, we have been well aware of the menace of zombie attacks. Theories vary about the exact mechanism of re-animation, and about the level of cognitive and sensorial impairment that it entails. Two things, however, are clearly demonstrated by a number of studies: (1) zombies are not as effective, in terms of perception and planning, as ther uninfected human relatives, and (2) infection is propagated to humans by physical, direct contact with zombies. Regarding the latter point, researchers diverge on whether simply coming in contact with bodily fluid (blood, salive) is sufficient to transfer the infection, or a full "zombie bite" is needed (in addition, of course, to the infected person dying so that she or he can be reanimated as zombie). On the other hand, zombies have been reported at times as extremely slow and clumsy (e.g., in [1]). While, lamentably, Zombology has not yet produced reliable reference works, nor even a systematic literature review, still one strategy to avoid the infection emerges from the above mentioned studies: leverage the limited range of behaviours exhibited by zombies, by providing them with purposefully engineering stimuli, in order to avoid direct contact and escape attacks.

In particular, [2] established the link between noise level and activity level of zombies. The author authoritatively arguments that zombies in their "unexcited" state would just stay idle, or mildly wander around, and do not appear to be

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[1] Pun intended.

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particularly aggressive. On hearing any sound[2], the activity level of zombies increases, in proportion to the loudness of the sound. With the activity level increases also their aggressivity towards humans, and their speed of movement and of attack. Indeed, despite the lack of proper statistical testing with a control group, the behaviour described above is depicted with such graphical evidence in documentaries such as [3] that little doubt about the validity of the relationship between noise and aggressivity level is left to the spectator.

We start in Section 2 by reviewing some relevant literature, and highlight the difference and novelty of our approach compared to earlier contributions. Section 3 then sets out the theoretical work for our model, and Section 4 presents the results of numerical simulations proving the effectiveness of the proposed strategies. Some conclusion and plans for future work complete the paper.

2 Related Work

Historically, our understanding of zombies has not always been accurate. The first ever zombie movie [4], misconstrued zombies as a sort of "golems", controlled by (evil) humans; we are well aware now that factually this is not the case. A more precise account was given by Romero in his classic trilogy, starting with [1]. Romero's behavioural model was then adopted by essentially all subsequent studies, up to the most recent ones, namely: [5] and its movie adaptation, [3]. In fact, in [3] and [6] the correlation between noise level, activation level, aggressivity and speed of the zombies is clearly presented.

Another related strand of research concerns the epidemiology of a zombie infection. Started by [7], the area has received increasing attention, till the latest results such as [8] that have even reached the mainstream audience.

The final thread we are bringing together in our work is about the behaviour of a *group* of zombies, which has been extensively studied (although usually not specifically with zombies in mind) under the label of *swarm behaviour*. A significant difference, compared to other studies, is that in our case each individual zombie is unaware of the presence (and behaviour) of other zombies in the area. They can only feel the presence of humans in close proximity (i.e., in their attack range), or establish the direction of any sound they perceive. In contrast, in most swarm models each unit in the swarm is aware of the position of all other units.

Specifically, in this work we set to develop a computational model of this particular behaviour, linking noise (emitted purposefully by humans) to zombie activation (that happens in reaction), and suggest strategies that can be used by unexperienced heroes in escaping, controlling, surviving, and ultimately defeating even large hordes of zombies. The model used in this paper is based on a more general model widely used in literature to describe the behavior of a set of autonomous and asynchronous entities that operate on a two dimensional plane: ASYNC (also known as CORDA) [9–11].

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[2] Apparently, zombies' senses of sight and smell are less effective than those of uninfected humans; hearing is much improved, whereas we have no information about their sense of touch, and prefer not to investigate that of taste.

One of the distinctive features of ASYNC is the absence of any explicit and direct mean of communication among the entities; in particular, communication happens implicitly merely by observing movements of the entities on the plane. A first attempt of modeling direct communication appears in [12], where the entities can communicate by turning on and off external bulb lights, i.e. lights visible to all entities. In this paper, we introduce for the first time, to the best of our knowledge, audio signals as a direct communication mean. The first important difference between lights in [12] and audio modeled here is that the intensity of the audio signal emitted by an entity decreases following the inverse-square law. The second main difference with the common features of ASYNC is that the entity the perceives the audio signal will move with a speed that is proportional to the perceived intensity (inversely proportional to its distance from the source): in all previous works in literature, the speed of the entities never changes during the execution of the protocols.

3 The Computational Model

We consider two kinds of entities: the *Humans* (H), and the *Zombies* (Z).

The Humans. We model our fellow humans as deliberate, asynchronous, resourceful agents. In particular, they can act according to pre-agreed plans, can observe their surroundings (including the positions of zombies and other humans, but not how excited the zombies are), and can move (within limited speed and range) and yell (i.e., emitting sound of a desired intensity). They cannot directly communicate with each other, but may have memory (hence, they can trace the trajectories of other agents, and execute plans that are articulated in several steps) and identities (i.e., they may discern who other humans are). Finally, they all share the same world coordinates, so that knowing the pre-agreed plans, and observing the current situation, they can act based on expectations of what the behaviour of other humans will be.

Overall, Humans are quite powerful agents, much better endowed than the Zombies, as we will see in Section 4. Any direct match between our resourceful Humans and the brainless Zombies would thus be very uneven, except for two (relatively minor) details. First, Humans can die, whereas Zombies cannot. In fact, in this paper we will assume that death is a final occurrence for a Human (other choices include turning the Human into a Zombie, or turning the Human into a Body which can be either disposed of by other Humans, or turn into a Zombie after a suitable incubation period). Second, Zombies are substantially more numerous than Humans. In many cases, we will study a scenario with a single Human and many dozens of Zombies, which seems to be the situation that most frequently occurs in documented (filmed) encounters.

Our investigation will thus try to answer a pressing question: if you or your family are confronted with an horde of zombies, which plans can you enact, alone or in concert with others, so that you can survive and possibly trick the zombies into adopting some desirable behaviour?

The Zombies. The Zombies are modeled as simple and *dumb* units; in particular, they are *autonomous* (that is they operate without a central control or external intervention) and *asynchronous*, and are driven by *sensing* the noise emitted by the humans. A Z has an *activity level*: at minimum activity level the zombie is in a quiet state, and does not move; otherwise, it moves towards its *current target* with a *current speed* proportional to the activity level. The activity level itself is increased in proportion to the total amount of noise perceived by the Z, and the current target is determined based on the direction of the noise.

A Z also has an *attack range*. If a H enters the attack range of a Z, it is assumed that the Z will snatch at, and overpower, him or her in a single movement. The outcome is usually unpleasant from the H's point of view.

The Z has no memory whatsoever, and is thus totally *oblivious*. Additionally, the Zs have no kind of agreement on their coordinates (i.e., no global compass is available), and have no means to directly communicate among them. In other words, the Zs move by just perceiving the noises emitted by the Hs.

The *cycle of "life"* of the Zs is described in Figure 1. At each cycle, each Z first *Look*s for the presence of any human in its Attack Range (AR), and retrieves their positions, stored in set H; in case H is not empty, the Z will move towards him/her and *bite* him or her. Then, the zombie *Hear*s the noises emitted by the humans; each noise is modeled by a vector whose direction is that of the source, and whose magnitude is proportional to the noise intensity. Based on perceived noises, the zombie calculates its Perceived Noise Level (PNL) as the sum of the intensities of all noises it perceives. A zombie can perceive noises that are being emitted at the exact time it is hearing: in other words, we do not model decay of the sounds in relation to time, but only in relation to distance (in particular: we do not model echoes, which in reality might be a useful tactic for Hs).

Based on PNL, it redetermines the Current Activity Level (CAL) and the Current Speed (CS); thus, it computes the destination target, and moves towards it. In determining the updated activity level, we consider anattenuation function, obtained through successive divisions by a constant *decay rate* > 1 (see Figure 1).

Initial Conditions and Termination. At the beginning we assume that the humans are emitting no noise, i.e., there is silence, that the Zs occupy all arbitrarily distinct positions in the environment, and that there is no human in the attack range of any zombie. Also, we assume that the activation level of the zombies is at their minimum[3]. Our game ends as soon as one human enters the attack range of a zombie and gets bitten.

4 Problems

In this section we propose several survival tactics that the Humans should actuate in order to not be bitten by the Zombies; all of them have been tested by numerical simulations, using the *Sycamore* simulation environment [13]. Given the gruesome nature of the material, we recommend only readersaged 18+ to

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[3] Note that this state can be always reached by humans not emitting any noise until the zombies reach their minimum activation level.

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ZOMBIE'S CYCLE OF LIFE
  $H$ := Look within my attack range $AR$;
  If $H \neq \emptyset$ Then
     BITE them;[a]
  Hear noises;
  $PNL$ := Sum of the levels of the perceived noises;
  If $PNL > CAL$ Then
     $CAL := PNL$;
  Else
     $CAL := CAL/DecayRate$;
  $d$ := Vector sum of all perceived noises
  $CS$ := Compute current speed based on $CAL$;
  Move towards $d$ with speed $CS$.
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[a] Different models can be defined, based on whether all humans in H are bitten, or just one of them – e.g., the closest. In our problems, we try to save *all* humans, and consider that Hs have lost as soon as one of them is captured: hence, the choice is immaterial in our context.

Fig. 1. The cycle of "life" of a zombie

continue with the paper — and, above all, not to try to replicate our experiments without experienced supervision and emergency rescue personnel at hand!

In order to be able to test the effectiveness of the survival solutions proposed in this paper, we model the Humans as entities that are able to asynchronously and independently move on the plane, following the ASYNC model [9–11]. Their aim is that of driving the Zs by emitting noise, trying to not become *too close* to the Zs. In particular, at any point in time, a H is either *active* or *inactive*. When *active*, a H executes the following three operations, each in a different state:

(i) *Look*: The human observes the presence of zombies and other humans in the environment. The result of this operation is a snapshot of the positions of all entities (both Hs and Zs) in the systems.
(ii) *Compute*: Each H executes the algorithm (the same for all Hs), using the snapshot of the *Look* operation as input. The algorithm they execute is related to the particular effect they want to achieve on the zombies' population, and will be detailed in the following sections. The result of the computation is a destination point and a *noise level*. The emitted noise is persistent; i.e., their audio device is not automatically turned off at the end of a cycle.
(iii) *Move*: The human moves towards the computed destination by emitting a noise at the computed level. If the destination is the current location, the human stays still, performing a *null movement*.

The Hs are modeled as powerful units; therefore, they can access unbounded local memory, they all agree on a common coordinate system (i.e., they agree on compasses), and they have unlimited visibility (i.e., when they *Look*, they can retrieve the positions of all Hs and Zs in the environment). The sequence *Look-Compute-Move* forms the humans' *cycle of life.*

In the following, we will denote the *diameter* of the zombies as the maximum distance between any two zombies, that is $\max_{i,j} dist(Z_i, Z_j)$.

4.1 Gathering

The first problem considered is the Gathering: the aim of the humans is that of having all the zombies gathered in a sufficiently small area of the plane. In particular, the humans consider the task achieved when the diameter of the zombies is smaller than a given distance ρ.

One Human. First we consider the case of just one human, and any large number of zombies.

Unhappy ending. If the human just emits sounds (continously or repeatedly), not moving, then he or she will be clearly be bitten by the zombies; thus, he/she just waits for the inevitable end. That is, we can state that

Theorem 1. *If a H emits a sound undefinitely and does not move, the H will be caught (eventually).*

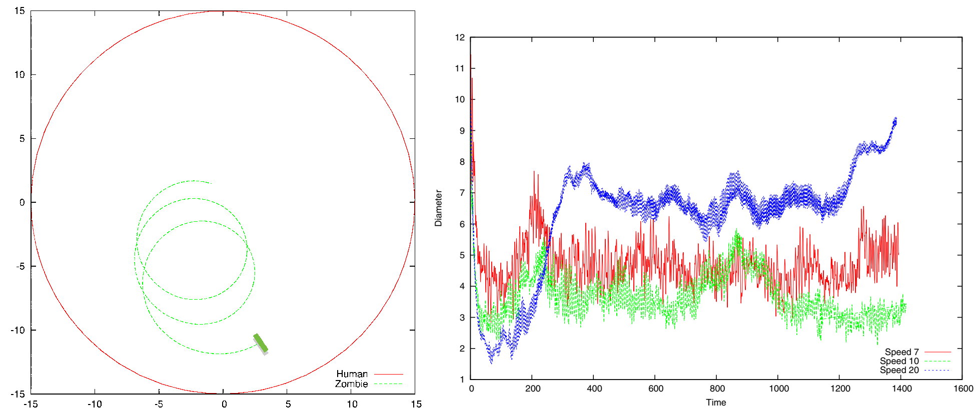
Of course, a definite duration of sound may not always be fatal: in fact, if the initial distance between the H and the Zs is sufficiently large, and the cumulative duration of the sound sufficiently short, it may well happen that the Zs' CAL decays to quiet before they reach the H. The exact outcome depends on the CAL decay function: if it reaches the minimum in a finite amount of time, then perfect quiet (and a still form of safety) can be achieved. If on the contrary the decay function has just an asymptote at 0 (as in our model in Figure 1), then even a finite positive amount of sound stimulation (i.e. any sound, no matter how brief) will lead to a final capture of the H.

The previous theorem stresses that a *clever* strategy must be decided by the Hs to successfully survive the Zs and achieve the task; in other words, the Hs cannot just use *any* strategy. An unwise choice of strategy will lead to a unhappy ending.

Happy ending. Thus, by previous Theorem 1, the lonely human needs to move in order to be able to survive the zombies, and to complete the gathering task. In particular, H can use the following simple strategy:

Protocol HappyGathering

1. H computes a circle centered in the centroid of the initial zombies' positions, and having radius larger than the diameter of the zombies.
2. H moves on this circle, continuously emitting a sound having constant intensity.



(a) (b)

Fig. 2. HappyGathering. (a) Traces of H and 1 zombie. The dash in the lower part of the diagram marks the starting position of the zombie. (b) Variation in time of the diameter of the Zs group with respect to different velocities of the leader.

Undergoing continous aural stimulation of varying direction will "trap" the Zs into a spyraling pattern, as shown in Figure 2(a)[4].

Because of the asynchronous nature of our model, no hard guarantee can be given as to the final outcome of this protocol. In fact, a H could emit a sound (as part of his or her strategy), and then just be *inactive* long enough for the Zs to reach him, without ever getting to the second action prescribed by the strategy.

Lacking theoretical guarantees, we use numerical simulations to understand the critical factors for success (and survival). Figure 2(b) shows the diameter of the Zs group varying in time. All other parameters being the same (in particular, the radius of the circle chosen by H is 5 times the diameter of the zombies), three different speeds for the H are shown. At speed 7, a satisfactory confinement is achieved, at an average diameter of 5. At speed 10, better confinement at diameter 3 is obtained. But beyond that at speed 20, the Zs move in a more chaotic manner (most probably, the randomness inherent in the asynchronous model plays a more important role, the faster the orbit is performed), only achieves a diameter of around 9, and risks "breaking up" the confinement.

It can be noted in all three simulations, that a pulse appears in the diameter of the Zs group. The frequency of the pulse is in part given by the orbital period of the H, and in part to semi-chaotic mareal effects, where small asymmetries in the initial distribution of the Zs can be amplified by resonating with the H's orbit. Figure 2(b) testifies that the choice of parameters can lead to rather different outcomes. A fuller analysis being out of scope for this introductory work, we limit ourselves to state the following

Observation 1. *If a H is "fast enough" and starts in a "favourable" configuration, the H can survive.*

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[4] In the interest of clarity, only the trace of one of the many Zs is plotted in Figure 2(a); all other Zs have similary trajectories.

Observation 2. *Showing that two different H behaviours lead to different outcomes for the same problem, shows that H's deliberations are significant, and that our work is relevant.*

Multiple Humans. The case of multiple Hs (usually a small number) and any large number of zombies, which apparently would seem to favour the Hs, actually proves itself to be more complicated.

An obvious extension of protocol HappyGathering would see the n Hs placed initially along the same circle as in the previous case, regularly spaced at $\frac{2\pi}{n}$ angles. Given that our Hs have a shared coordinate system, can freely communicate among themselves (presumibly, by gestures!), and that initially all Zs are in perfect quiet, we can assume that in every non-degenerate initial configuration, the Hs can reach the desired configuration prior to emitting the first sound. Notice that we can have degenerate initial configurations, e.g. when one of the Hs is totally surrounded by Zs whose attack ranges overlap, leaving him or her no possible escape. To such configuration, our only reaction would be, "though luck". However, simulations show that a straight n-gon solution does not work. Indeed, instead of being more closely packed, the Zs end up being partitioned into n different groups, each getting closer and closer to one of the Hs, until they get too close.

It is interesting to notice that while a single human orbiting around the Zs has a packing effect, $n > 1$ humans orbiting cause the opposite behaviour. We will turn back to this problem in Section 4.4.

We have not found a protocol to solve the Multiple Humans Gathering problem so far (except by reducing it to the Single Human variant, where other Hs simply try to stay out of harm's way and let "the hero" do the job).

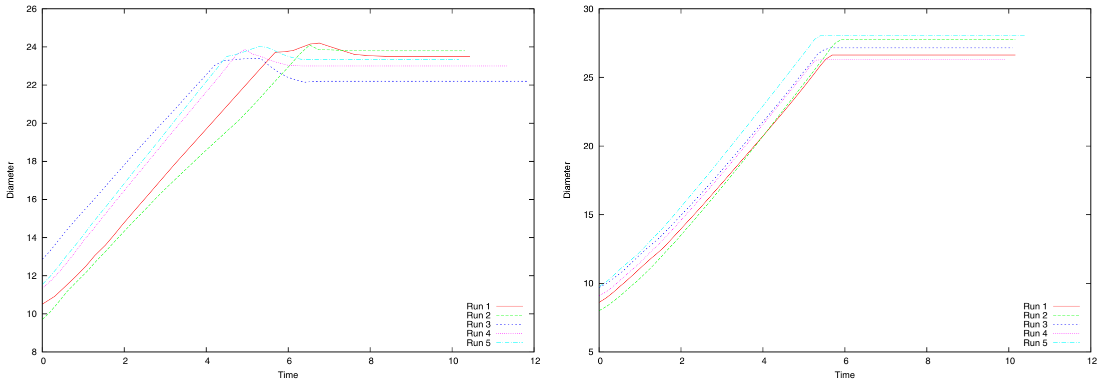
4.2 Flocking

With the Flocking, the Hs aims at bringing the Zs to a designated target area, while keeping them compacted. The idea in this case is as follows:

Protocol Flocking

1. The H gathers the Zs following Protocol HappyGathering.
2. When the Zs are *close enough* (i.e., the diameter of the zombies is smaller than ρ), the H starts moving linearly towards the target area, while keeping the circular movement of Protocol HappyGathering.

Alternatively, the protocol can be thought of as a variation on HappyGathering where the H's movement is computed according to a pure circular motion, if the diameter of the Zs group is larger than ρ, or as the composition of a pure circular motion and a linear "step" of length σ towards the target area, otherwise. This second formulation, being a single stateless protocol, highlights the self-stabilizing properties of the solution.



(a) (b)

Fig. 3. Outcome of few runs of StillSpreading, with starting n-gon of the Hs having (a) diameter 15 and (b) 18. In these experiments, 6 Hs have been employed.

It is easy to see that, provided a sufficiently small σ, at each linear step the offset σ is absorbed back due to the packing properties of HappyGathering demonstrated in the previous section. The validity of the result is also shown by numerical simulations, which we omit here for brevity.

4.3 Spreading

In this scenario, the zombies are grouped somewhere, and the goal of the humans is to spread them. We consider two different variants of the problem:

Separation. The task is achieved when the distance between the closest pair of Zs is greater than a given distance ρ. In particular, we can define a condition of *passage* as requesting that there is a safe passage for Hs between any two zombies (i.e, $\rho > 2AR$).

Diameter. The task is achieved when the diameter of the group of Zs is greater than a given distance δ.

Note that the spreading operation is crucial in case the humans want to create a safe path through the population of the zombies, avoiding the risk of being bitten. We propose two different strategies to solve the problem.

Still Humans. The first strategy is quite simple: the humans stand still, continuously emitting sound.

Protocol StillSpreading

1. The n humans compute the n-gon that surrounds the zombies, and place themselves on its vertices.
2. The humans start emitting sound at a constant intensity.

Obviously, as also stressed by previous Theorem 1, the effectiveness of this strategy depends on how large is the n-gon the Hs decide to place themselves on at the beginning: If it is sufficiently large, we may expect that the SPREADING task can be successfully achieved; otherwise, the Hs will be bitten. Also, the same consideration about the CAL decay function apply; the protocol only works if Zs stand still once their CAL reaches a minimum.

In fact, numerical simulations show that the Diameter variant of STILLSPREADING always succeeds, provided a sufficiently large initial n-gon. An intuitive explanation can be given as follows: since the n-gon is centered on the centroid of the Zs group, two Zs at opposite ends of the group (i.e., the two that define the current diameter) will be more attracted towards humans placed on opposite semi-n-gons, and hence their separation will further increase. For any ρ, a sufficiently large n-gon will do the trick. As an example, in Figure 3, we reported the outcomes of few runs of STILLSPREADING with 6 Hs; in (a), the diameter of the starting n-gon of the Hs is not sufficiently large, and all curves show a drop, representing the moment where the humans get bitten, hence their diameter decreases correspondently (recall that, when a H gets bitten, he/seh cannot yell anymore, hence the Zs reach their quiet state). In contrast, in part (b) of the figure, the diameter of the starting n-gon of the Hs is larger, and the STILLSPREADING technique always succeeds: When the desired spreading has been reached by the Zs, the Hs stop emitting sounds, the Zs reach their quiet state and their diameter does not change anymore.

In contrast, the Separation variant will in most cases fail. The explanation is as follows: the two closest Zs in the group will be lying very close to each other, hence they will receive almost the same noise stimulus, and thus will move towards the same H. Their distance will thus decrease at each step, so that the desired Separation is never achieved, and eventually they will reach and bite the (still and noisy) H closest to them.

Mobile Humans. In this second approach, the humans move in order to produce a more effective spreading strategy: first, they want to limit the radius of the polygon where they start from; second, and most important, they want to decrease the chances of being bitten by the Zs. Thus, as already observed for the GATHERING case, they need to move. We suggest the two following strategies:

ONESPREADING: After the placement on the initial n-gon, when a human realizes that a Z gets too close to him/her, he/she starts to move radially away from the center of the initial n-gon. That is, a H moves away from the group of Zs only if necessary.

CIRCLESPREADING: As before, when a human realizes that a Z gets too close to him/her, he/she starts to move radially away from Z. However, here, when a H starts to move away, also all the other Hs do the same, even if there is no Z too close to them. In other word, in this case the Hs try to be always stationed on the vertices of a regular n-gon.

While both variants solve the problem, as usual under appropriate values of the parameters, our numerical simulations show that CIRCLESPREADING is

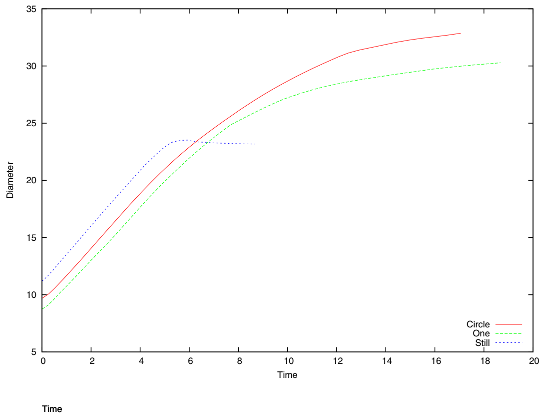


Fig. 4. Average values of the three proposed solutions for Spreading with respect to Diameter. In these set of experiments, the diameter of the starting n-gon of the Hs is 15 and $n = 6$.

somewhat more efficient at the task. In Figure 4 we present the average Diameter values over a number of runs for all three scenarios, with 6 Hs: (S) StillSpreading, (O) OneSpreading, and (C) CircleSpreading (the diameter of the starting n-gon of the Hs is 15). While in all cases with (S) the Hs do not reach their goal (here, the (S) curve is the average of the runs shown in previous Figure 3(a)) and the Hs never make it to time $t = 6$, the moving variants progress indefinitely, with ever-increasing diameter, and with (C) achieving a larger diameter than (O) at any given time t. Hence, (C) reaches a desired diameter ρ faster than (O).

4.4 Splitting

We have observed in Section 4.1 that an n-humans orbiting configuration fails at causing a faster packing, and instead tends to split the Zs group in n sub-groups, each moving towards one of the n humans. While this behaviour does not realize a gathering, it can be used to obtain a Splitting.

In Splitting, which is a variant of Spreading, we request that there is an assignment of Zs to n groups such that the diameter of each group is no greater than a given constant σ_1, and the separation between groups (that is: the minimum distance between two Zs which are members of different groups) is no smaller than another constant σ_2.

5 Conclusions

Zombology is not for the faint of heart. In an asynchronous environment, much is at stake, and being *inactive* when one would had better be *active* might be the difference between survival or extinction of the human race.

We believe that the various problems we have presented, and the suggested solutions with corresponding simulations, will be a useful contribution when — not if — the zombie outbreak arrives. Until that day, our models also introducea novel framework for signaling between autonomous robots, extending to sound the light-based signalling introduced in [12]. It is worthwhile to remark that sound-based communication and the notion of activation level, with its impact on speed and long-lasting effects due to decay, substantially change the scenario. In particular, our models sport second-order effects that are not found in first-order mechanism (such as light and constant-speed linear movements). Also, different strains of zombies might exhibit different behaviours, e.g. a were-zombie could head towards the closest noise source, or the loudest one, instead of being equally attracted by multiple sources, as in our model. Such variants will need to be studied in future work, if we want to be prepared for any new outbreak.

We dedicate this work to the many lab assistants that were harmed in the making of this paper. Running experiments with Zombies can be a tricky business, and while we acknowledge that numerical simulations may never be an adequate substitute for field experiments, yet after a number of such failed experiments we came to the conclusion that we prefer the safety of tenure-track, to the risks of a zombie startupper life.

To all the H instances that willingly gave their life in hundreds of simulations for the progress of Science, goes our unbounded gratitude.

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