Playing with Dynamic Systems - Battling Swarms in Virtual Reality

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Abstract. In this paper, we present a serious game with the goal to provide an engaging and immersive experience to foster the players' understanding of dynamic networked systems. Confronted with attacking swarm networks, the player has to analyse their underlying network topologies and to systematically dismantle the swarms using a set of different weapons. We detail the game design, including the artificial intelligence of the swarm, the play mechanics and and the level designs. Finally, we conducted an analysis of the play performances of a test group over the course of the game which revealed a positive learning outcome.

Keywords: Swarms · Boids · Network Dismantling · Serious Games

1 Introduction

The complex structures of real world systems in different areas of research and engineering have long been presented as networks, e.g. in empirical studies [12], in biological systems [20], social sciences [26], or information technology [35]. Graph theory allows us to analyse the topologies of these networks, to investigate how they evolve and to reveal how we could manipulate them. According analyses considered, for instance, the robustness of power grids [13], the interplay of the world's air traffic [32], or the spreading of computer viruses [25]. Effective dismantling strategies [7], that determine which edges to cut or nodes to knock out in which order, can help to slow down or even stop according, negative spreading phenomena [1], as also witnessed during certain phases of the coronavirus pandemic [34].

Swarms [2] can be understood as networked systems whose components' interactions result in volatile topologies [22]. Due to their spatially well-presented dynamics, swarms are perceived as lively and are considered as subjects or means of artistic expression [23,6] as well as of numerous academic and commercial computer games [21]. Building on these works, we set out to harness the interactivity of swarms in a computer game as well, and highlight (parts of) the relationship between their topologies and dynamics.

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It has been questioned in the past, whether serious games, with goals other than mere entertainment [15], need to be as much fun as commercial video games [30,8]. We aimed at providing both, an insightful and fun play experience. Learning from the great success of the serious game “America’s Army” [19], we designed the game as a first-person shooter (FPS) as well, tasking the player with the goal to dismantle swarms of flying robots. In [9], we presented a brief overview of the game’s mechanics. We decided on a virtual reality (VR) game as it has been shown that immersion can generally foster player performance and learning results [11] and because target acquisition and pointing, the basic interaction task of an FPS, is performed significantly faster in VR, as well [18].

The remainder of this paper is structured as follows. In Section 2, we provide an overview of relevant research on networks, network dismantlement and networks in games. In Section 3, we explain the concept and design of our developed game. In Section 4 we present a preliminary empirical study we conducted to analyse the game’s effectiveness in terms of learning about network structures and dismantling. We conclude this paper with an outlook on possible future work.

2 Related Work

Initially, we had to decide on which kinds of networks we wanted to expose to the player. Therefore, we will briefly provide an overview of widely researched network topologies before elaborating on the concept of network dismantling. We will conclude this section with a brief introduction to related computer games.

2.1 Network Topologies

Topologies describe the patterns of node interconnections in networks. Different topologies lead to different network properties. So-called *scale-free networks* have a power-law distribution of connectivity values (degrees) among their nodes, i.e. these networks consist of many nodes of low and few nodes of high degree, also referred to as hubs [3]. With the great probability of randomly choosing a single node of low degree comes robustness against loss of random nodes. However, targeted attacks against hubs can easily break scale-free networks into smaller networks [31]. A scale-free network collapses when as few as 5 to 15% of its hubs are destroyed [3]. *Star networks* with only one hub connected to all the other nodes maximally stress the discrepancy between low and high degrees, which is why we also introduce this topology in the game. This is one of the most common topologies of computer networks [29]. *Grid networks* have a matrix-like structure, where each node is connected to its fixed set of neighbours. Instead of having a small number of hubs that are primary targets for dismantling, in grid networks all the nodes have the same degree (up to the grid’s borders). For our game, we focused on scale-free and grid networks as they are rather distinct.

2.2 Network Dismantling

Network dismantling is the process of finding a set of nodes whose removal from the network results in the fragmentation of the network into subcritical network components at minimal overall cost [27]. Finding the most efficient way to dismantle a network is NP-hard. For large networks this implies that there is no algorithm that can reliably find the optimal solution. But there are heuristic approaches that can efficiently find good solutions [33]. The underlying metrics of these heuristics can be the degree of a node and its betweenness centrality, with the latter achieving better results. The betweenness centrality describes the number of shortest paths between every pair of nodes of the network that run through the given node. Further efficiency improvements can be achieved when updating these values throughout the dismantling process.

2.3 Networks in Games

There are digital games that fundamentally rely on network structures. In [21] several academically motivated examples of games involving swarms were summarised and a taxonomy was suggested considering the level, target and granularity of control as well as modalities including view, interface and time of interference.

Given its indisputably adverse goal, many stores removed the game Plague Inc: Evolved [24] temporarily from their offering list. Here, favouring pathogen spread is the goal and to eradicate humanity. Although the network of air travel plays an important role here, the player is focused on driving the evolution of pathogens to be most effective. The opposite, and thus much more humane, goal is pursued in the browser game VAX [10]. The player can stop viral spread in a turn-based setup by vaccinating and quarantining persons that are at risk of infection. Despite this rare example of network dismantling in games, most of them deal with building and maintenance of networks, also in other domains such as colonization, e.g. Anno 1800 [5], or in abstract contexts as in Planarity [14], a browser game that challenges the player to unravel a planar graph.

3 The Game's Design

In the presented VR FPS, the player is approached by swarms of attacking, flying robotic units. They assault by dropping bombs or by performing heads-on kamikaze attacks. A room-scale VR experience, having ported a first prototype from the HTC Vive to the Oculus Quest head-mounted display (HMD), immerses the player in a virtual environment. There is no form of locomotion other than moving in real-life. The player can step out of the line of attack, duck for cover or shield himself. Attack is, however, the best defense in the given context and a variety of ballistic weapons are at his disposal. The player can recharge his health and ammunition, if he succeeds in clearing and picking up resource packs from the swarm robots. The continuous motion and intermittent attacks of the enemy swarm combined with the different opportunities of interaction (Fig. 1) result in a generally fast paced gameplay and open a vast space of interwoven parameters for level design. Especially the arrangement of peaks and plateaus of the pace often correspond closely with the difficulty of the game.

3.1 The Swarm

The enemy swarms move based on the boids model [28] that considers each swarm member an agent that decides on its movement based on its neighbors. Boid agents follow three simple urges, i.e. avoidance of collisions, alignment with their neighbours and separation from neighbours that come too close. For the purpose of our game, we added additional rules (Fig. 2): (a) the maintenance

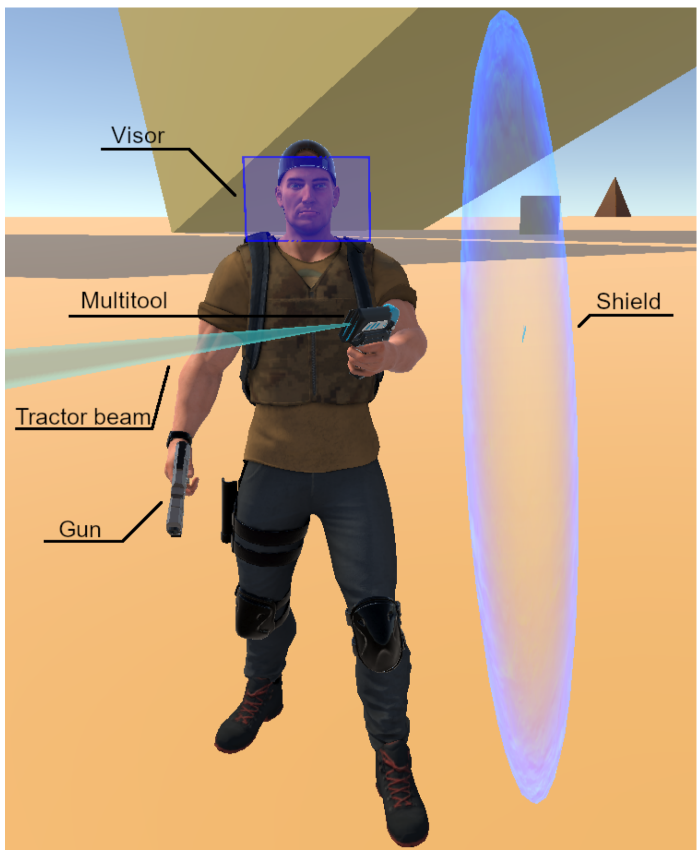


Fig. 1. This image shows the player's avatar, holding a gun in his right hand, a multitool in his left hand. The latter can emit a tractor beam to attract falling perks, put up a shield (circular, blue) and project an augmented visor field that reveals the swarms' topologies (rectangular, blue).

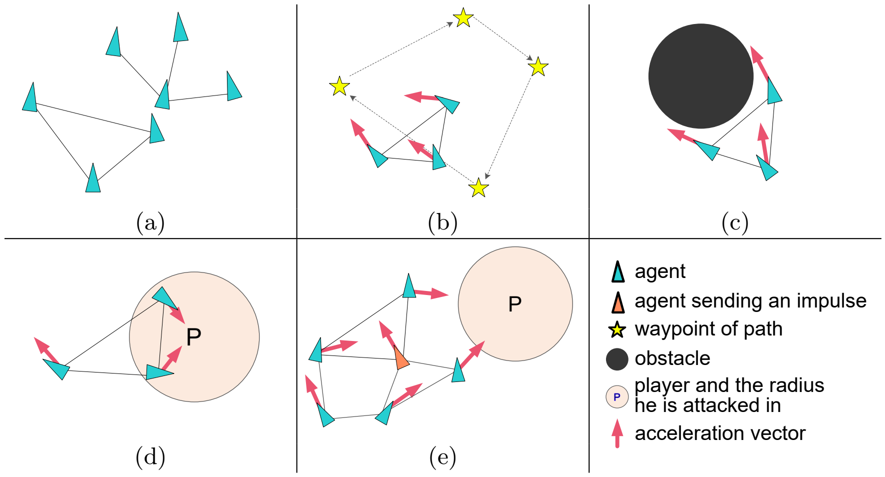


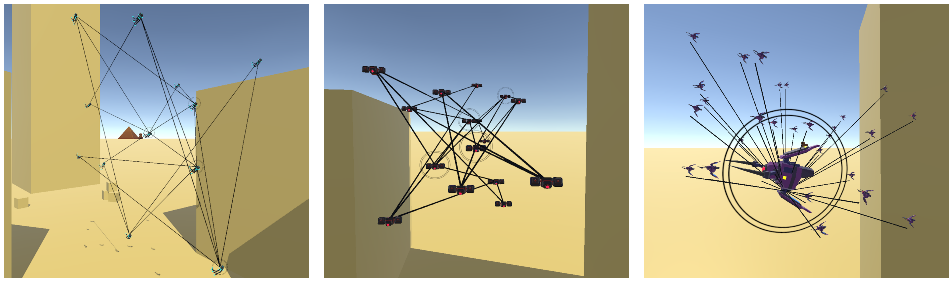
Fig. 2. (a) Boids consider pre-defined network connections, (b) follow a given path, (c) avoid obstacles, (d) attack the player, when they are near him, and (e) can send an impulse to their directly connected boids, which triggers an attack from them.

of assigned neighbor connections in accordance with an a priori-determined network topology (Section 2), (b) following a given path through the environment, and (c) avoiding collisions with objects on this path. Concerning their hostile manoeuvres, (d) swarm agents attack the player when getting close. In addition, (e) each agent also has a small chance to trigger an attack by its neighbors. Such triggered attacks will not terminate until the player suffered damage or successfully shielded himself. We introduced this mechanic in order to stress the greater influence of hubs in the network, as higher degrees of swarm agents immediately translate to greater chances of triggering neighbor attacks, emanating greater threats.

Due to the addition of multiple rules, for all rules R, the normalized results r of each independent rule had to be multiplied by their respective weights w to result in the desired direction vector d (Eqn. 1).

$$d = \sum_{i=1}^{R} r_i \cdot w_i \tag{1}$$

We designed three types of enemies with varying proximities and network topologies (Fig. 3): (a) Tentacle agents form scale-free networks and maintain great distances. (b) Bee-like Sting agents form grid networks and keep close to each other. (c) There are small and large Pin agents. The large ones can sustain large amounts of damage and are surrounded by smaller Pins to form star networks. As stated before, targeting the hubs allows the player to fight scale-free networks effectively. The most effective way for the player to dismantle star-networked swarm is targeting its only hub. On the other hand, grid networks



(a) (b) (c)

Fig. 3. (a) Tentacle bots form scale-free networks, (b) Sting bots grids, and (c) Pin bots star networks.

have no specific point of attack and force the player to develop a more elaborate fighting strategy.

3.2 The Play Mechanics

An important part of the challenge for the player is to identify and attack weak spots in the enemy swarm and to make good use of the available weapons: (a) A pistol with low, 1*sec* shot frequency but infinite ammo (Fig. 4), (b) a grenade launcher with high impact, ponderous 3*sec* frequency and very limited ammo resources (Fig. 5), and (c) a sub-machine gun with high 0.125*sec* shooting frequency and, consequently, fast ammo depletion (Fig. 6). While (a) and (c) increase the damage of swarm agents to knock them out individually, (b) affects not only the primarily hit agent but also its immediate neighbors in the network. The shooting task is assisted by the display of a trajectory arc. Such aiming augmentations have proven very effective in VR to support shooting tasks [17].

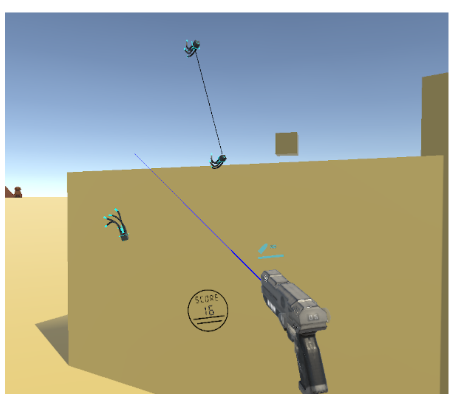


Fig. 4. Pistol

Fig. 5. Grenade launcher

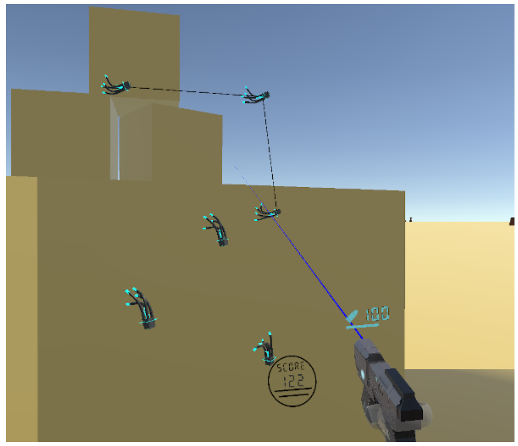


Fig. 6. Sub-machine Gun

To further assist the analysis of and interaction with the swarm network, a multitool (Fig. 7) is attached to the other controller which makes one of the following functionalities available at a time: (a) Extend a round *shield* to deflect swarm agents on a collision course. If the agents become aware of the shield early enough, they dodge and stop their attack. If used for too long, the shield needs to recharge. An according “energy”-bar hovers above the multitool. (b) Shoot a *tractor beam* to pull new weapons, resource packs, or swarm agents towards the player. The traction on the agents is inversely proportional to their network degrees. (c) Activate a *visor* that displays the network’s edges between the swarm agents (Fig. 8). In addition, agents of high degrees are encircled. At the beginning of the game, this display is always on. But this comfort feature breaks down later in the game and the player has to activate the visor manually by holding the multitool next to his head. In this way, the player has to actively decide which multitool functionality is best in any given situation.

Fig. 7. Health and shield status float above the multitool to keep the player informed at all times.

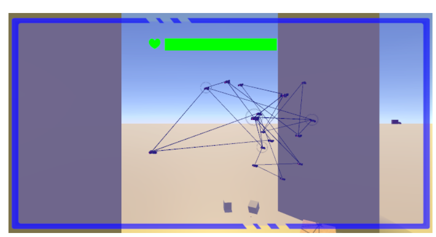


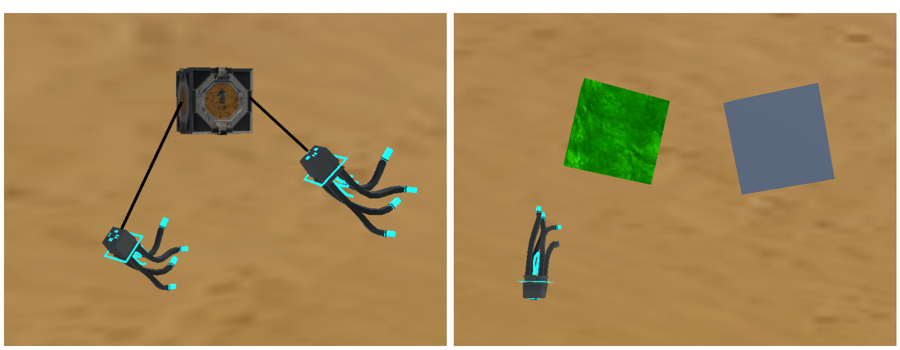
Fig. 8. The visor augmenting the player’s view with network information.

If the player's health value drops to zero, the game is over. To recover from suffered attacks, he has to pick up health packs. Resource packs are collectively carried by subsets of agents of the enemy swarm, i.e. the packs are connected to several agents and if those are taken down, loot boxes drop to the ground as well. While within reach, the player can pull the packs towards him and pick them up using the tractor beam, restoring health or ammunition. If, by accident, the player shoots any of those lootboxes (Fig. 9), they are destroyed. He, therefore, has to diligently distinguish between different nodes in the network and dismantle it carefully—in analogy to, for instance, freeing hostages in military operations, releasing non-infected persons in handling disease spread, or maintaining vital functions in economic or biological systems.

3.3 Level Design

Several tutorial levels ease the player into the game by explaining the basic interaction mechanics, effects of weapons and the required resource management. Each level of the game follows the same routine: A swarm flocks along a given path and attacks the player when in his vicinity. The player uses his tools and whits to destroy the swarm. Taking an enemy out results in a death animation of the swarm agent and text feedback with the achieved score for this takedown. When all the connections of a swarm agent are cut by knocking out its neighbours, the agent also becomes dysfunctional and falls to the ground. When the whole swarm is destroyed, the level is cleared and the player is challenged by the next of 12 levels in total. As pointed out in Section 2 optimally dismantling a (swarm) network is not an easy task but it ensures that (a) the player receives high scores and (b) his odds of survival rise.

In the first level, the player can only use the multitool to learn to shield himself. It is the only level that utilizes very small enemies that are destroyed upon contact with the shield. The second level introduces the pistol, the third level the grenade launcher (and switching weapons), the fourth level the sub-machine



(a) Lootbox (b) Resource Packs

Fig. 9. A lootbox (a) drops resource packs (b) when cut loose from the swarm network.

gun, and the fifth one lootboxes. In level eight, the player's visor experiences a malfunction. Its previously always-on display of network information has to be manually activated from now on. An appropriate tutorial is provided. Level nine is special as a Pin agent in star network formation together with 30 light-weight agents occurs for the first time. Here, sustaining lots of damage and neighbor attacks become decisive mechanics. From level ten onward, the player has to battle two swarms at the same time. In level ten itself, the second swarm spawns after a 10*sec* delay, which gives the player the opportunity to focus on the first swarm but also provides for a surprise. In subsequent levels, the swarms spawn at the same time.

Fig. 10 provides an overview of the level design. We organised the level progression to incrementally teach the game mechanics. Increasing the numbers of swarm individuals and swarms increases the difficulty of the game aiming at better flow and learning effects. Starting the game with a fully functioning visor shows the player the importance of the underlying network topologies. The required manual activation starting in level eight makes the player experience the lack of these crucial information and re-enforces their strategic utilization.

4 Evaluating Dismantling Apprehension

In order to examine whether playing the game improves one's abilities to efficiently dismantle networks, we measured 15 players' (12 male) performances. Thirteen of the test persons were students, two of them were employed in retail. They were between 20 and 28 years of age (M = 22.5, SD = 2.23) and played games for about 11 hours a week on average (M = 11.36, SD = 8.94). Three of the participants had never worn HMDs before. On average, they had used HMDs for about 40 hours (M = 40.30, SD = 57.27).

We followed the following procedure: After welcoming the participants, they filled out a demographic questionnaire. Next, they were introduced to using the HMD and its controllers. The participants were advised to ask the experimenters

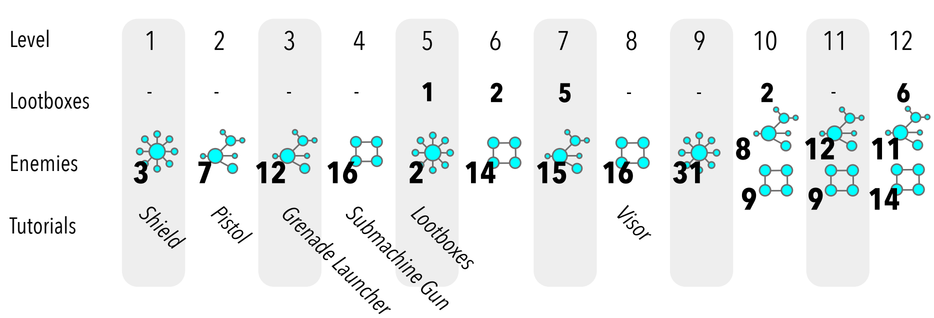


Fig. 10. Lootbox information, number of enemies and tutorials of each level. The enemies' topologies are represented symbolically as well: Star, scale-free and grid networks are first encountered in levels 1, 2, and 4, respectively.

for help, only if they could not accomplish a task by themselves. Then, the participants played the game, which lasted about $15min$. The experimenters watched the progression on a laptop and took notes. In case the participants were not able to complete all of the levels, they were not asked to replay the game. After playing, the participants were instructed to take off the HMD. Finally, they were asked by one of the experimenters, whether they had used different fighting strategies for the different opponents.

In order to evaluate the performance of the participants, we calculated two different measures, f_{bc} and f_{deg}. With increasing difficulty, both values decrease or remain steady, only if the subject's skill of dismantling networks increases. f_{bc} (Eqn. 2) is the arithmetic mean of the differences of the highest betweenness centrality $max\ g(n) \in [0..1]$ yielded by node n_{max} and the betweenness centrality of the node destroyed $g(n_h)$ at discrete hit h, whereas $hits$ denotes the set of nodes hit over the course of one level.

$$f_{bc} = \frac{\sum_{h=1}^{||hits||} g(n_{max}) - g(n_h)}{||hits||} \tag{2}$$

We calculated the measure f_{deg} analogously (Eqn. 3), considering the nodes' degrees $d(n)$, normalized by the maximal degree throughout a whole level, i.e. $\hat{d}(n) = d(n)/max\ d(\underset{n_h \in hits}{arg\ max}\ d(n_h))$.

$$f_{deg} = \frac{\sum_{h=1}^{||hits||} \hat{d}(n_{max}) - \hat{d}(n_h)}{||hits||} \tag{3}$$

As the measures signify differences from the best possible dismantling strategy, smaller values indicate greater impact of the shots. We calculated both f_{bc} and f_{deg} because the nodes with the highest degrees are highlighted in the game, but they do not necessarily coincide with the nodes with the highest betweenness centrality. It has been shown that the latter is the better heuristic for efficiently dismantling of a network [33], but the degree is more directly observable in the game. We, therefore, investigated whether there was a difference between using f_{bc} and f_{deg} for rating the player's performance.

The topology of a swarm remains fixed until the player removes an agent/node from the swarm/network. Therefore, the measures f_{deg} and f_{bc} did not consider the time it took to take down the enemies, reaction times, weapon usage or tactics. Rather, they rate the realisation of a specific dismantling strategy, i.e. how well the player can decide which enemy should be attacked in a concrete situation. There is an optimal way to play each level, but considering the large interaction space (the states of the player and the swarm, the weapon used, the target hit, etc.), it is only of theoretical value. Therefore, the given measures only consider the optimal target at the time of a hit.

We excluded hit lootboxes from the calculations, as these nodes were not hostile. The measures were not applied to levels one and five because all the interactions in these levels were guided tutorial tasks. Level nine was excluded because it is the only network with the star topology and it does not support the analysis of performance improvements. Additionally, we calculated the correlation between the measures and the usage time of the visor ("visor up-time") by means of Pearson's correlation coefficient, starting with the proactive use of the visor in level eight.

Figure 11 shows the connectivity of swarm individuals in a given level after a given number of shots. As a result, the diagrams reveal the degree distribution established at first and how the players' shots changed the topology quantitatively over time. The initial degree distributions in grid networks peak at 3 as most agents are at the perimeter of the swarm, few are inside the grid (4 neighbours) or in the grid's corners (2 neighbours). The scale-free networks are created based on the Barabási-Albert model [4]: First, two nodes are generated and connected. Next, a new node is added to the network at a time and connected to already existing nodes with a connection probability proportional to the existing nodes' relative degrees. Statistically, this procedure results in a scale-free degree distribution. The degree distributions shown in Figure 11 deviate in that boids with a degree of 1 cannot exist due to the game's mechanics. In addition, the initial distributions of the different levels are fixed across multiple runs to ensure a consistent game experience.

In terms of the evolution of degree distributions, one can see that levels featuring scale-free networks show higher standard deviations than those featuring grid networks. Grid networks have no immediately favourable point of attack such as the hubs in scale-free networks. Therefore, the attack strategy has a smaller influence. A plausible explanation for this difference is that the discrepancy between the players' analytical skills or knowledge is more pronounced in levels featuring scale-free networks.

In Figs. 12 and 13, the mean values with standard deviation of f_{bc} and f_{deg} are plotted in the context of the levels' difficulty. Due to the high standard deviations, there is no visible improvement or deterioration in any of the measurements throughout the game. But the difficulty of the game increases with each level due to more complex interaction mechanics, and the rising numbers of enemies and swarms as detailed in Figures 12 and 13. In particular, we calculated the difficulty according to Equation 4, whereas t denotes the type of the underlying network topology (weighted with 1 for star networks, 2 for grids, and 3 for scale-free and mixed swarms), n_{agents} the number of agents of the attacking swarm(s), n_{loot} the number of lootboxes in a level times the corresponding weight w_{loot} (weighted with 4) and on whether the player has to activate the visor manually, or not (encoded in variable v, weighted with 20). The values for n_{agents} and n_{loot} are shown in Figure 10. The values and their influence on the difficulty expressed in Equation 4 roughly correspond with the difficulty introduced by these respective game elements that we perceived during their formative development.

$$difficulty = t \cdot n_{agents} + w_{loot} \cdot n_{loot} + v \tag{4}$$

As Hamari et al. [16] stated, an always challenging game endorses learning. The fact that there is no significant change in the calculated scores indicates

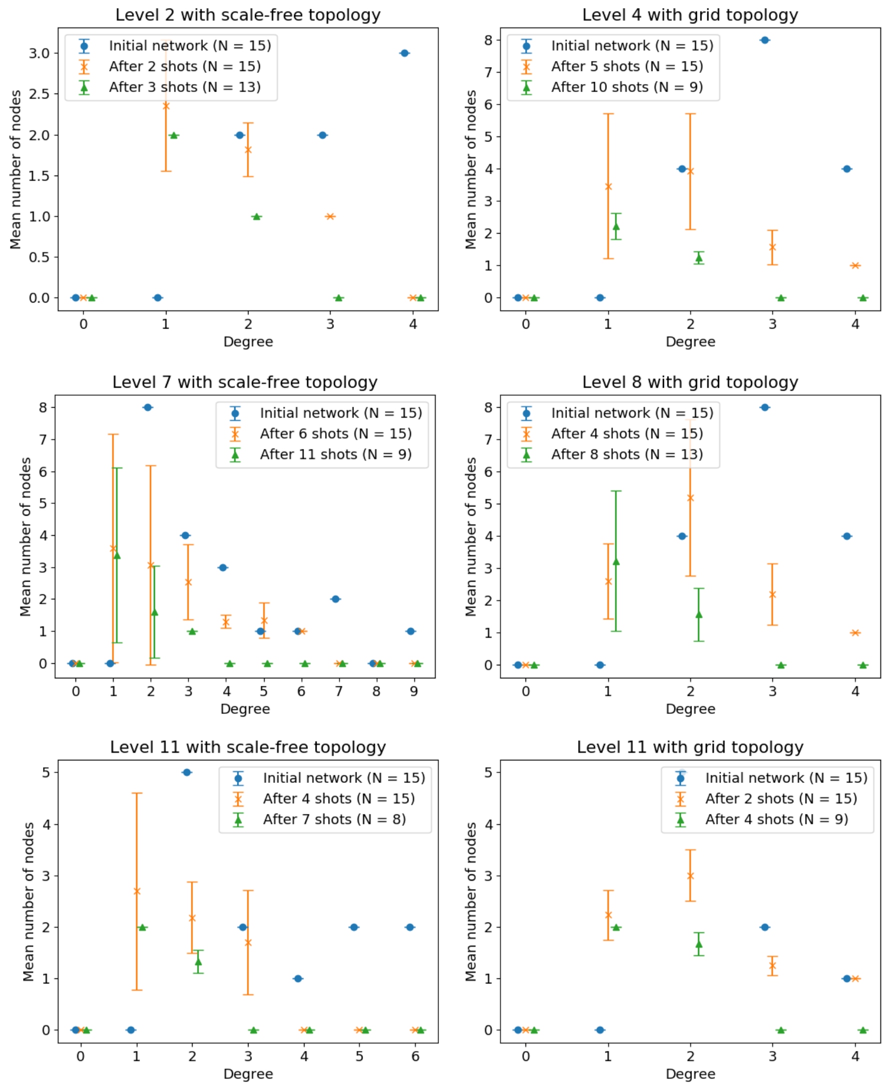


Fig. 11. Degree distribution of the mean number of nodes with the standard deviation at the initial network state, intermediate state and at the state before most players had completed the level. The left graphs show levels with scale-free networks and the right graphs show levels with grid networks.

that the player's performance, and therefore his knowledge about dismantling networks, improves proportionally to the rise in difficulty.

When asked about their fighting strategies, most participants pointed out differences in the behavior of the boids in the star network compared to the other formations. They reported that they focused on the central hub to destroy

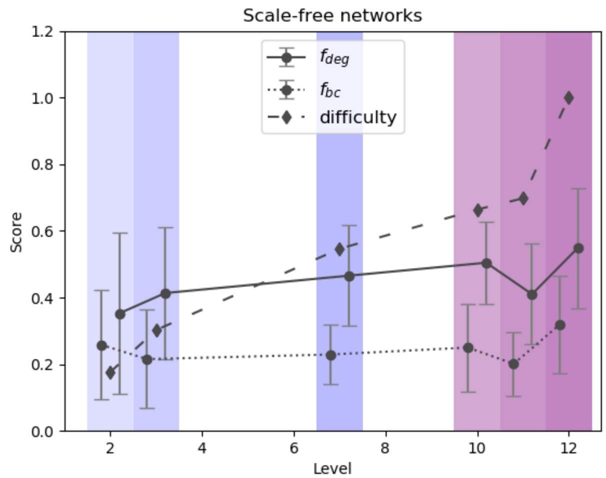


Fig. 12. Scale-free networks: Mean with standard deviation of f_{bc} and f_{deg}, and difficulty for the given levels. Intervals shaded in blue show levels featuring swarms in scale-free formation. Those in purple show levels featuring grid networks and scale-free networks. Here only scale-free networks are presented. The shades' opaqueness reflects the levels' difficulty. For clarity in the diagram, the values of the difficulty have been normalized based on the maximum difficulty value.

the network. This was validated by the game logs that show that the shots were almost exclusively on the central hub. A few participants were able to detect and specifically indicate that the Sting agents flew in closer proximity and changed directions simultaneously, whereas the tentacles flew further apart and moved more independently. One subject reported that he focused on the tentacles because they were easier to defeat. No further strategic deliberations were reported.

5 Summary and Future Work

In this paper, we presented a computer game featuring swarms as lively, interactive networked systems. The players' performances in dismantling the swarms increases with play experience. The difficulty of the levels of the game is balanced to always challenge the players to a similar extent, resulting in a desirable gaming experience and fostering the learning outcome. As the proposed performance measures do not consider the players' reactivity or resource management but only capture the gain from hitting an individual node at a time, we suggest that the players' performance improvement may be tied to an improved knowledge about network dismantling and the exposed network topologies.

As a result, the contributions of this paper include the concept of a serious game for training network dismantling, the design of swarms with fixed network

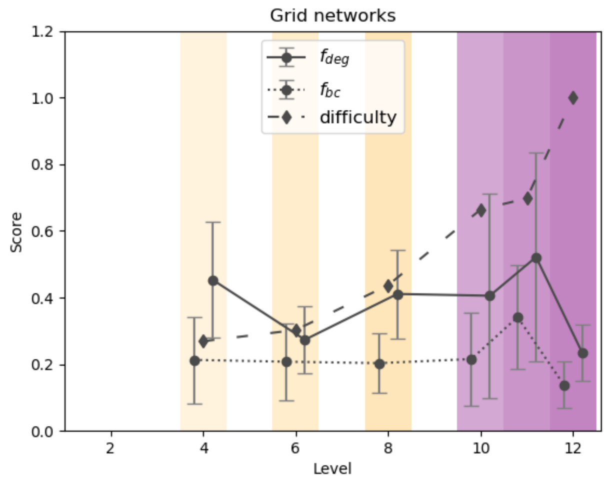


Fig. 13. Grid networks: Mean with Standard Deviation of f_{bc} and f_{deg}, and difficulty for the given levels. Intervals shaded in yellow show levels featuring swarms in grid formation. Those in purple show levels featuring grid networks and scale-free networks. Here, only grid networks are presented. The shades' opaqueness reflects the levels' difficulty. For clarity in the diagram, the values of the difficulty have been normalized based on the maximum difficulty value.

formations, the integration of non-hostile, preservable nodes, various means of interaction with the networked swarm agents, as well as a flow-inducing level design that drove the gameplay, as well as the introduction of evaluation scores to measure the players' performance.

Our next steps will include further development of the game, including greater numbers of swarm agents, more complex networks and a longer overall playtime. A release through popular distribution channels is planned, especially as we hope to gain a greater size of contributors to larger-scale playtests in this way. It would open up the possibility to further survey the learning effects of the game. In this context, a longer-term study of learning apprehension and tests of explicit factual or procedural knowledge, as well as knowledge transfer could be incorporated, also considering, for instance, in-game questionnaires.

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