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Cellular Automata Approach for Crowd Simulation

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(Rigorous Thesis)

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I hereby declare I wrote this thesis by myself, only with the help of referenced literature.

. . . .

Abstract

This thesis sums up relevant problems and explain current existing solutions to the topic of crowd simulation, behavioral control and use of cellular automata for these problems. Some of the terms in this thesis does not have explicit definition, and we define them axiomatically.

Moreover, we propose solution using cellular automata for crowd animation in three different situations. Firstly, cellular automaton with rules similar to Conway's Game of Life is used for the movement control of the participants in a crowd. This situation is similar to situation of dancing performance, or dancing at the disco, where motions are more random.

Secondly, we use cellular automaton for the control of the movement and behavior of the individuals in the flash mob situation, where flash mob is spread to the new participants similarly as social preferences, or disease. Rules for this automaton are unique and also simple perception system is used, where rules are view depend.

Thirdly, core of this work and probably future extensions are in behavioral control over the crowd in the virtual environment, more specific, exhibition environment and population of virtual museum. Based on cellular automaton and more advanced level of behavior, such as collision detection and avoidance is possible. Therefore we use cellular automaton for behavior control and also movement in the environment. Behaviors are specific for this environment, therefore we discuss psychology based behavioral patterns for this situation and apply them for use in cellular automaton.

KEYWORDS: behavioral animation, crowd simulation, cellular automata, virtual museum

Abstrakt a Resumé

V tejto práci sa zaoberám riadením a simuláciou davu pomocou celulárnych automatov. V prvej časti definujem základné pojmy z oblasti simulácie davov, nastavovania správania a vnímania prostredia. Niektoré z týchto pojmov sú dobre definované v inej literatúre, ktorú používam ako zdroj, niektoré však nemajú exaktnú definíciu, sú chápané len intuitívne, preto je potrebné tieto pojmy dodefinovať. Na toto dodefinovanie používam axiomatický aparát. Ďalej vysvetľujem základnú problematiku celulárnych automatov ako aj ich použitie pre simuláciu davov. Zároveň poukazujem na niekoľko najviac používaných typov správania pre simuláciu davov.

V druhej kapitole predstavujem základné problémy v tejto oblasti a ich čiastkové riešenia, ktoré ponúkajú ostatné práce. Jedná sa hlavne o základné práce v správaní skupín, od ktorých sa odvíjajú ďalšie moderné články. V tejto sekci predstavujem aj základné delenie prístupov pre riadenie davu. Jedná sa o mikroskopický a makroskopický prístup. Prvý sa vyznačuje tým, že riadenie skupiny je spravené pomocou nastavenia správania a pohybu jednotlivcov. Tým, že sú týmto jednotlivcom nastavené správne hodnoty a správanie a umožnené interagovanie s ostatnými členmi a prostredím, je vlastne nastavené aj správanie celého davu. V tomto prípade ide hlavne o prístupy využívajúce tzv. **agentov**, kde agent predstavuje jedného člena skupiny, je schopný vnímať okolie ako aj vykazovať rôzne modely správania. Na druhej strane makroskopický prístup riadi jednotlivcov pomocou nastavovania hodnôt celého davu. Sem môžme zaradiť celulárne automaty a sociálne sily. Makroskopický prístup je vhodný pre detekciu kolízií, ako aj pre priestorovné vnímanie okolia. Zároveň prináša manipuláciu davu ako celku. Mikroskopický prístup zase na druhej strane dovoľuje nastavenie správania jednotlivca a tým prináša prirodzenejšie správanie, pretože jednotlivec môže vykazovať originálnu personalitu. Väčšinou sa tieto prístupy kombinujú pre vlastnosti, ktoré sú popísane vyššie a práve toto kombinovanie môže tiež prinášať rôzne problémy.

Medzi tieto práce patrí správanie kŕdľov [Rey87], [Rey99], kde autor predstavuje tzv.

flocking behavior, ktoré je základným modelom, ktorý sa používa nie len pre kŕdle, ale aj iné skupiny živých bytostí. Jedná sa o prístup, kde je skupina riadená pomocou správania agentov.

Ďalším pozoruhodným prístupom je nastavenia pomocou tzv. **sociálnych síl** [HM95], kde dav je riadený silami podobne ako by išlo o sily, ktoré riadia pohyb vody. Tieto sily však niesú založené na fyzikálnom svete, ale na vzťahoch a správaní ľudí.

V nasledujúcich sekciách predstavujem rôzne prístupy, ktoré vylepšujú základné metódy. V prípade celulárnych automatov sa jedná najmä riešenie pohybu, ktorý je neprirodzene diskrétne a navyše sa vyskytuje problém s rýchlosťou nakoľko diagonálny smer je rýchlejší ako ostatné. Tento je možné riešiť zjemnením mriežky [SHT10]. Ďalším problémom je nastavenie správania jednotlivca, teda rôzne prístupy k vyhýbaniu sa zrážkam [DDW06], resp. tzv. **lokálne pravidlo**, ktoré umožňuje pohyb jednotlivca podľa jeho okolia a stavu jednotlivcov v tomto okolí. Jednotlivci sa vždy snažia ísť za svojim cieľom najvhodnejšou cestou a spotrebovať čo najmenej energie, resp snahy, čo nazývame **algoritmom najmenšej snahy(least effort)** [SHT09].

Nasledujúce dva prístupy využívajú výhody celulárnych automatov tým, že používajú delenie priestoru do pravidelných mriežok. Jedná sa o tzv. **podlahové pole (floor field)** [LM03], **pole potenciálov (potential field)**. Oba prinášanú davu globálnu informáciu o prostredí, kde v prvom prípade ide o vzdialenosti k zaujímavým bodom, napr. východom a v druhom prípade o sa k tejto informácii ešte pridávajú aj stopy, ktoré zanechávajú jednotlivci za sebou.

Pri simulácii davov je viacero problémov ako len detekcia kolízií a nastavenie správania. Pokiaľ chceme realistický dav, zaujíma nás aj pohyb jednotlivcov a samotná vizualizácia davu. Častokrát našim cieľom je vytvoriť heterogénny dav [TM07], či už vo vyobrazení jednotlivcov, alebo v ich pohybe. Pokiaľ ide o pohyb, jeho ručné generovanie by bolo neúnosné. Existujú však metódy na nové generovanie pohybov z už existujúcich pomocou štruktúry tzv. **grafov pohybu (motion graphs)** [KGP02] ako aj ich prenesenie na nové postavy [Gle98]. Pokiaľ ide o pohyb davu taktiež existuje grafová štruktúra, ktorá napomáha spájaniu viacerých sekvencii a nazývame ju **graf skupinového pohybu (group motion graph)**[LCF05].

Animácia skupiny davov nemusí byť vhodná len na skúmanie správania davov, napríklad pre identifikáciu problematických miest pri evakuáciách v čase nebezpečenstva, ale môže nám aj prinášať vizuálne zaujímavé efekty vytváraním rôznych tvarov pomocou správnych pozící jednotlivcov ako aj ich pohybu [TYK+09], [XJY+08].

Pokiaľ ide o nastavenie správania davu, je dôležité vhodne si zvoliť situáciu, pre ktorú chceme toto správanie simulovať, aby sme vedeli poskytnúť jednotlivcom len tie informácie, ktoré by aj v reálnom živote dostali. Teda zvoliť zhodný model percepcie ako aj vstupných systémov. V moderných metódach je aj snaha o simulovanie pamäte [SMK05]. Najčastie sa využíva problematika chodcov [BEHG11], [SMK05], [LM03], [BKSZ01],[BA00] preto ich model správania je najviac popísaný. Ostatné situácie nemajú dobre popísaný model správania a preto simulácia davov je vlastne multidisciplinárny problém, kde je okrem umelej inteligencie nápomocná aj psychológia. Rovnako ako správanie, v moderných prístupoch je aj snada o verné nasimulovanie ľudských emócií [AA02], tento problém však ešte nenachádza postačujúce riešenia.

Vo štvrtej kapitole sa zoberám vysvetlením troch nami navrhnutých celulárnych automatov, ktoré čiastočne riešia rôzne problémy v simulácii davov. Prvým z nich je celulárny automat, ktorý riadi pohyb jednotlivcov v dave pomocou podobných pravidiel ako sa nachádzajú v hre Život [Weib]. Týmto riadením prináša automaticky generovanú sekvenciu pohybov, ktorá sa dá využiť napr. na rôzne tanečné davové scény.

Druhý celulárny automat riadi správanie aj pohyb jednotlivcov v dave s využitím jednoduchého percepčného modelu, kde pravidlá automatu sú závislé na uhle pohľadu pozorovateľa. Tento automat je využitý pre scénu, tzv. **flash-mob**, kde niekoľkí účastníci začnú na verejnom priestranstve vykonávať zrazu niečo šialeného (v našom prípade začnú tancovať) a ostatní sa k nim začnú pripájať a práve toto pripájanie je riadené celulárnym automatom so špeciálnymi pravidlami.

Tretí celulárny automat riadi správanie a pohyb davu v prostredí výstavnej sály s istými predpokladmi, ako že dav je riedky, že ide o priestranstvo bez úzskych chodieb, atď. V tomto priestore sa návštevníci automaticky pohybujú, snažia sa dosiahnuť cieľ, ktorým sú väčšinou exponáty, alebo východy, v prípade exponátov sa pri nich snažia chvíľu zostať. Pri týchto aktivitách sa zároveň menia hodnoty, ktoré menia správanie jednotlivcov, podľa ich preddefinovanej personality. Práve v ďalšom riešení tohto automatu a presunutím do priestoru múzea by sme sa chceli venovať v ďalšej práci. Priestor múzea je z hľadska správania a vyhnutia sa zrážkam zložitejší ako výstavná sála, lebo sa v ňom nachádza viacero užších chodieb. Zároveň bude nutné hlbšie preštudovanie problematiky múzea z pohľadu psychológie [RSS+28].

Na záver je nutné podotknúť, že sme v práci navrhli tri odlišné celulárne automaty pre odlišné problémy riadenia davu, avšak všetky tri sú originálne vo využití celulárnych automatov pre danú problematiku, preto ešte ponúkajú priestor na zlepšenie a v budúcej práci by sme chceli toto zlepšenie priniesť.

KĽÚČOVÉ SLOVÁ: animácia pomocou správania, simulácia davu, celulárne automaty, virtuálne múzeum

"Animation can explain whatever the mind of man can conceive. This facility makes it the most versatile and explicit means of communication yet devised for quick mass appreciation." Walt Disney

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1 Introduction

We try to answer in this chapter questions why are crowd simulations interesting, why is research in this field interesting and why we use cellular automata instead of other options. Work in crowd simulation is multidisciplinary, because for a successful simulation also psychological theories need to be incorporated. In the next chapters we explain basic terms and methods that are needed for this topic (chap. 2), describe related projects, their pros and cons (chap. 3), propose our solution (chap. 5) and in the last section we suggest possible problems that should be solved in the future (chap. 5).

1.1 Why Crowds?

Crowds are interesting from many points of view. Firstly, a crowd of human beings brings life to the scene, not only virtual, but also to real. Crowds are everywhere around us, especially in public places, humans are accustomed to perceive other humans. Space that is filled with crowd is more natural and less sterile. When we see in virtual world crowd of other humans, or even other living beings we feel more comfortably, we are not alone in an empty space.

Secondly, participants in a crowd can act separately, can have own behavior, visual system. Participants can behave in a way that they seems to have their own will. On the other hand, crowd acts also as a whole, where behavior is similar among participants. Decision of a proper mixture of these two behavioral principles (individuals and crowd as a whole) makes crowd simulation interesting, as it is hard to measure the quality and optimize the solution to be more or less visually pleasant.

On the other hand, crowd is not only visually attractive and make observers feel more comfortably but also various crowd simulations could be use to identify emergency risks of different environments. Examples of these risky situations are emergency exit bottlenecks and weight tests. Essential in these problems is testing before emergency occurs, identify possible future problems and bring better solution before real emergency happens.

Many research groups are interested in crowd simulation [TM07]. There are many subproblems that should be solved and many of them have no satisfying solution. Main problems are realistic animation of human motion and realistic behavior. Both of them are hard because there is no precise model for these problems. For example dance is motion but is also a performance where dancer express emotions and feelings and it is not the same for different performers. Even walk cycle is one of the basic human motions, it is learned in basic animation classes. It also one of the hardest, because this motion is so many times seen by human eye, that even small divergence in acceleration is visible.

Moreover, human behavior understanding is not solved up to now. There are psychologists that try to understand behavior in various specific situations or even in more complex way. If there is no full description of behavior, it is hard to simulate. Therefore researchers try to simulate behavior in specific situations in very constrained form, that should be sufficient for the problem. Finding new situations where it is not already simulated and try to solve the problem there is goal of many modern approaches. Holy grail in this field is to simulate very complex and universal solution of human behavior with emotions, both individual and collective.

1.2 Why Cellular Automaton?

Cellular automaton are grid based solutions that formalize certain models in the regular grid. Cells of this grid than have states that change in discreet time steps. More precise definition is in section 2.2. When space is divided in the regular grid, objects in the scene (obstacles and crowd members) are set to occupy this grid. Then it is very easy to find space relations between these objects under discreet topology with reduced neighborhood. Therefore finding neighbors in some defined proximity is easy and helps with obstacle avoidance and collision detection. Moreover when space relations are defined also behavior control is easier where other members or environment affect behavior of an individual.

These are main advantages of this approach. Conversely, there are also disadvantages, where solution is not straightforward and special techniques need to be find. This disadvantages are mainly in the motion, where motion along the grid has the same problems as other discrete solutions. This problems include smooth velocity change and smooth change in direction of movement. There are already some solutions, but these are not satisfactory. Another already known problem is using rectangular grid with Moore neighborhood (8-neighborhood), where step along horizontal or vertical direction is shorter than in diagonal directions.

Regardless the problems described here, we still think that use of cellular automata is powerful enough to solve some problems in crowd simulation control.

2

Terminology and Basics

In this chapter we would like to explain some basic terms, their definitions and explanation according to their use in this work. We also discuss here definition of Cellular Automata and their use for crowd simulation.

2.1 Definitions and Notations

In crowd simulation research there are some terms such as *crowd*, *agent*, *environment*, *simulation* and others, that are often vaguely defined, because their meaning is intuitively understandable. Therefore, d we would like to bring more precise definitions to prevent any misunderstandings.

2.1.1 Crowd

In this subsection we explain basic terms that are related to the crowd.

There are more definitions for the **crowd**:

Definition 1. Crowd *is usually defined as a large number of things or people considered together [PAB08].*

Definition 2. Crowd *is a large group of individuals in the same physical environment, sharing a common goal [MT97]*

Definition 3. *We use more exact definition and define* crowd *as a finite set of individuals that have defined collective behavior and share same environment. When term* Crowd *used in this thesis, it usually refers to a virtual crowd, see def. 4.*

Definition 4. Virtual Crowd, Member, Individual, Participant *are a crowd, member, individual, participant generated by computer, in computer and displayed on the display.*

Definition 5. Virtual Human *is computer generated representation of a real human with defined human-like geometry, movement, materials, textures, behavior and emotions according to description that is based on real human geometry, movement, materials, textures, behavior and emotions.*

For purposes of simulations and also of this work, sometimes *Virtual Human* refers to a an object without a geometry, textures, only behavior and emotions are defined. Geometry is then represented with very simple objects, such as sphere, or cube to better observe behavior.

Definition 6. *For purposes of simulations and also of this work, sometimes* Virtual Human *refers to an object without simple geometry, textures, only behavior and emotions are defined, according to the definition 5. Geometry is then represented with very simple objects, such as sphere, or cube.*

Definition 7. Participant, Individual, Member, Person *are single objects with defined individual behavior and emotions and have visual system to percept environment. These objects also have geometry, materials, textures and animation. When in set, they have ability to create collective behavior, therefore also a crowd. These terms as used in this thesis are synonyms and usually are referred to virtual participants, individuals, members, persons respectively.*

They have variety of properties that define their individuality. These properties define emotional states, behavior, but also velocity, disability, direction, goal, etc. This properties can vary depending on the situation.

Definition 8. Group *is a finite set of individuals that have defined collective behavior. These individuals are not humans-like.*

Definition 9. Pedestrian *is a person who travels by foot [PAB08]*

Definition 10. Flock *refers generally to a group of objects that exhibits polarized, non colliding, aggregate motion. The term polarization is from zoology, meaning alignment of animal groups [Rey87].*

Definition 11. Boid *simulated bird-like, bird-oid, even when they represent other sorts of creatures such as schooling fish [Rey87]. These creatures move in all three directions in 3 dimensional euclidean space and incorporate their own visual system.*

Definition 12. Virtual human agents *are humanoids, whose behavior is inspired by that of real humans, they are equipped with sensors, memory, perception and behavioral motor (enable them to act and react to events)[TMK00]*

2.1.2 Behavior

In this subsection we explain basic terms that are behavior related. While familiarity with the interdisciplinary research literature on emotion and behavior is important, arriving at some definition of emotion, behavior or other affect-related terms is much less important for those who examine this phenomena in the field of psychology. As psychology is an empirical science, its practitioners are generally uninterested in definition. On the other hand, the meaning of a concept in science is determined after extensive investigation of the phenomenon the term relates to, not before such an investigation [AA02]. However this is hard problem, for purposes of this work and also for algorithms finding it is important to have some definition. There are usually more definitions for the same term in this chapter, because of the uncertainty and lack of definitions indicates that the field is very new .

Definition 13. Behavior *is often defined as the way in which animals and humans act [TMK00].* Behavior *may be described in a hierarchical way. A level of the hierarchy containing several behaviors to be performed sequentially is called a behavior. Each behavior of a* behavior sequence *is called a* behavioral cell *[TMK00].*

- Collective Behavior *Is a set of specific behaviors of participants in crowd, that satisfy following condition:*
  - *are result of perception of the others*
  - *are common to all participants*
  - *result in sharing the same goal for all participants*
- Emergent Behavior *is a group behavior, where individuals acts in a way that will result in collective behavior.*
- Steering Behavior *is the ability to navigate around environment in a life-like and improvisational manner [Rey99].*
- Reflexive Behavior *is set of behaviors, that will result in obstacle avoidance [TT94]*
- Motivational Behavior *depend on the local variables of the individual (mental state, such as hunger, libido...) [TT94]*

Definition 14. Behavioral Animation *is an animation, where change of temporal values is defined according to the behavioral variables.*

Definition 15. *Many implementations of emotion are necessarily shallow because the systems in which they occur are not attempts to simulate a complete mind [AA02]. Therefore also definitions are distinct, depending on what for are emotions implemented.*

- Emotions *are a physical and psychological reactions to external and internal factors [JKF+11].*
- Emotions *may also be defined as the affective aspect of consciousness. An emotion is a persons reaction to a perception [TMK00].*
- Emotion *is a short natural algorithm that is unique to the individual and defines reaction to the situation, which consists of the set of the input variables from sensing system.*

Definition 16. Sensing System *is a set of variables that describe percept space and other behavior of other individuals. This systems and it's setting affect individuals behavior. Mostly known example of this system is Human Visual System, but in this work is not only visual and not only human system in consideration.*

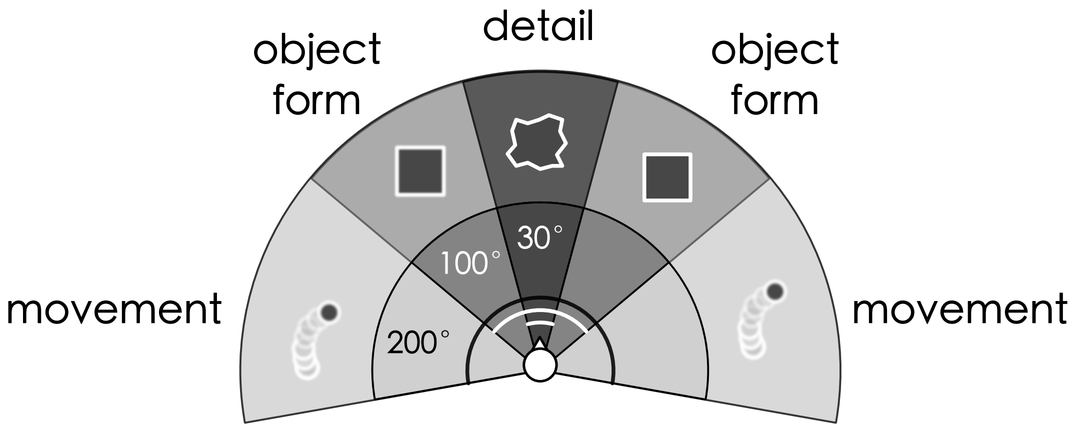


Figure 2.1: Horizontal perception model of a normal human. View from the top.

Definition 17. Perception *is defined as the awareness of the elements in the environment through physical sensation [TMK00].*

Perception of normal human *is as follows: Human horizontal perception field is divided into three main parts. The first part is defined by a vision angle of 30 degree. In this field a human can see object in detail. The second part is defined by a vision angle of 100 degree. In this part, a human can see only object forms. In the third part (Its vision angle is 200 degree), only movements of objects are seen [BEHG11].*

Above is simplified definition of Perception that is used for crowd simulation and is based on psychological studies and is shown on fig. 2.1.

Definition 18. Memory *is a set of information that describes previous time related events.*

2.1.3 Simulation

In this subsection we explain basic terms that are related to the simulation.

Definition 19. Simulation *is algorithmic description of phenomena based on precise mathematical theories. Phenomenon here is usually behavior.*

Definition 20. *In computer graphics,* Procedural *means created by automatic generation using algorithm description instead of manual input by the user. It is usually used for the modelling of well described objects, or for animation of fuzzy objects.*

Definition 21. Natural Algorithms *are algorithms designed by evolution over millions of years [Cha09]. These algorithms from our point of view include flocking behavior, crowd motion and others.*

Definition 22. Agent *is virtual participant that is controlled by automaton and incorporates sensing system, is aware of the environment and other participants, avoids collisions are acts according to the behavior. Agents and participants are usually synonyms in the crowd simulation terminology.*

Definition 23. Actor *is the computational abstraction that combines process, procedure and state [Rey87].*

Definition 24. Obstacles *are interactive objects in environment [TMK00].*

Definition 25. Collision Avoidance *is behavior that will affect motion of the participant and will result in non colliding with other participants and obstacles. It consists of other behaviors:*

- *When participant gets output from sensing system, it incorporates information about neighborhood, and* Collision Detection *behaviors process these information and result is knowledge of collisions.*
- Collision Prediction *is similar to Collision Detection, difference is that collisions in this behavior are predicted with use of higher range of neighborhood.*
- Obstacle Avoidance *is part of the collision detection, where only obstacles are avoided.*

Definition 26. Collidee *is part of a group of another actors near him with near velocity, same direction - collision avoidance of a whole group [RD05a].*

2.1.4 Environment

In this subsection we explain basic terms that are related to the environment.

Definition 27. Environment *is in this thesis and usually in other works 3 dimensional euclidean space that allows members to move and occupy space. Movement can be either in all three dimensions (for example birds, fish, etc.) or only in two dimensions (for example herds, humans, etc.) This two dimensional movement could be approximated with only two dimensional space. Environment includes crowd, obstacles and also other properties such as wind, water, magnetic force or other forces that affect crowd.*

Definition 28. Constrained Environment *is environment with constraints, that are usually space constraints that allow movement only in some parts. Example of this environments are pathways, or locked spaces, etc.*

Definition 29. Neighborhood *is a spherical, or circular zone of sensitivity centered at the individual's local origin [Rey87].*

When grid based approach is used, neighborhood *is also discreet and might be different for the cells. More about neighborhood specific for the crows simulation in the next section 2.2.*

2.2 Cellular Automata

In this chapter we would like to explain basic theory of cellular automata and their use in crowd simulation. When discussing cellular automata, firstly definition of automaton is needed.

Definition 30. Automaton *is self organizing abstract machine [Wol02].*

There are many different uses of automaton theory and these are mainly discussed in field of discrete mathematics and theoretical computer science. The type we use here is called cellular automata (sing. - cellular automaton, abbr. CA).

Definition 31. Cellular Automaton *(Wolfram) A cellular automaton is a collection of "colored" cells on a grid of specified shape that evolves through a number of discrete time steps according to a set of rules based on the states of neighboring cells. The rules are then applied iteratively for as many time steps as desired [Weia].*

Definition 32. Cellular Automaton *(Ferber) Cellular automata are discrete dynamical systems, whose behavior is completely specified in terms of a local relation [DDW06].*

Definition 33. Cellular Automaton *(Weimar) Let us take into consideration four elements: (L, S, N,f), where: L - Set of cells of the lattice, S - Set of states, N - Set of neighbors, f - transition function. Additionally, a configuration* $C_t : L \rightarrow S$ *is defined as a function, which associates each state with a grid cell. An equation of change of a configuration is shown by the equation below with the supplement.*

$$C_{t+1}(r) = f(\{C_t(i) \| i \in N(r)\}), \tag{2.1}$$

where:

- $N(r)$ *- set of neighbors of cells* r
- r *- current cell number*
- t *- discrete time step* $t = t + 1$
- i *- single cell*

$$N(r) = \{i \in L \| r - i \in N\} \tag{2.2}$$

It seems to be a very simple model that is not suitable for solving complex phenomena. On the other hand S. Wolfram presents in his book [Wol02] a large collection of problems that could be solved using cellular automata. Mostly they are various time-depend biological systems, natural algorithms, or textures that describe various phenomena of living beings where their irregularities could be successfully represented by CA. Also crowd behavior is one of the natural algorithms and could be represented by CA in theory. The only problem is in finding a suitable definition of this special CA.

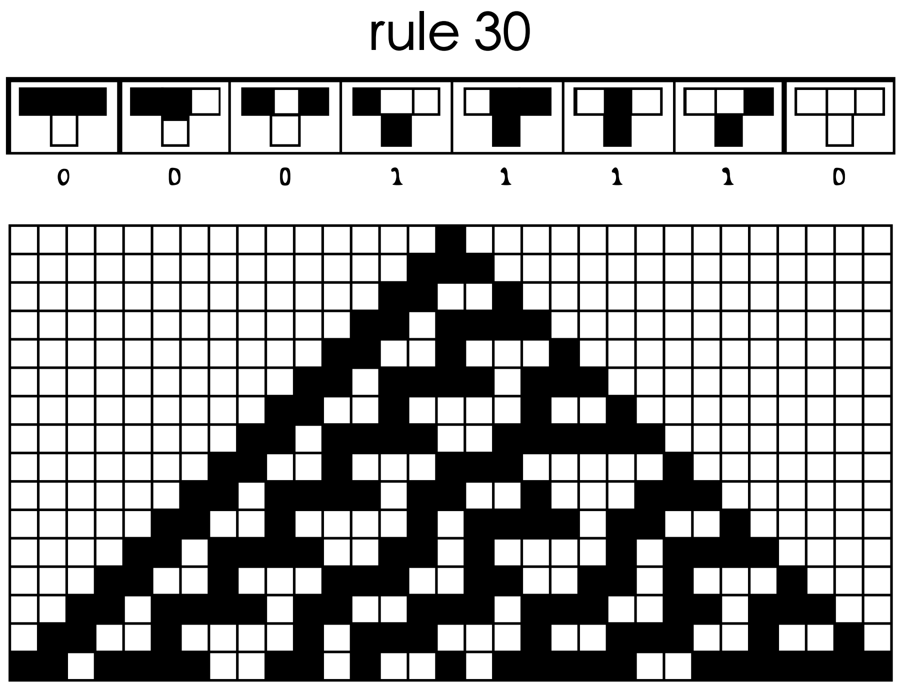
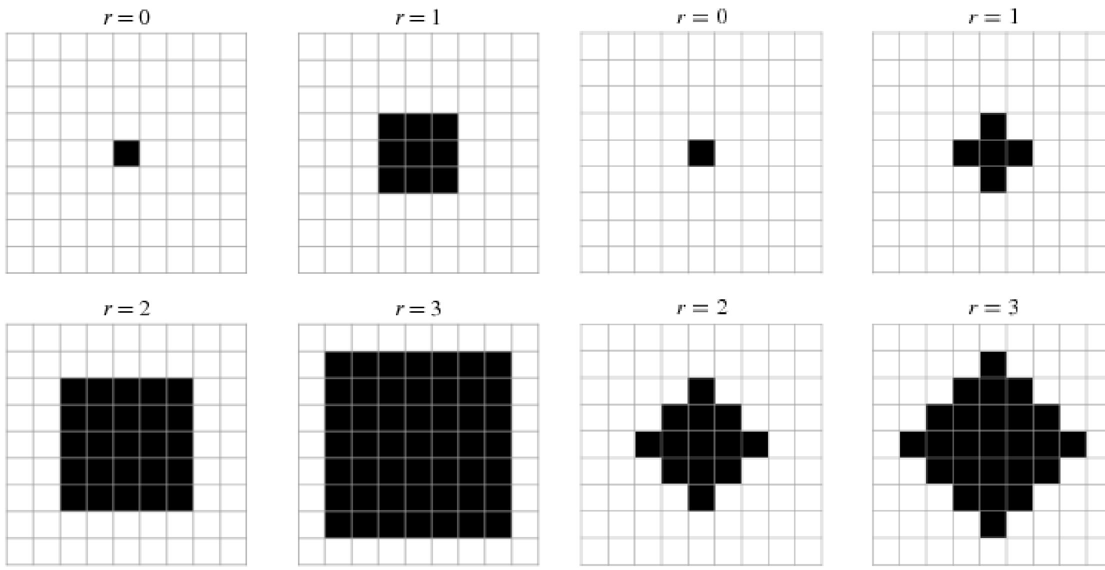


Figure 2.2: Transcription rules for Rule30 starting from the single black cell [Weia]

The simplest type of automaton is known in one dimensional space, where finite number of rectangular cells are used and colors of the cells are only black and white. Starting condition is set (values 0 for white, 1 for black coloring) and in discreet steps values of the cells are changed according to the neighborhood (neighbors are only left and right). Even such simple CA have amazing properties. There are 256 such automata, each of which can be indexed by a unique binary number whose decimal representation is known as the "rule" for the particular automaton. An illustration of rule 30 is shown in fig. 2.2 together with the evolution it produces after 15 steps starting from a single black cell [Weia].



(a) (b)

Figure 2.3: Neighborhood in regular rectangular cellular automaton. (a) Moore's, or 8-neighborhood [Weic], (b) von Neumann's, or 4-neighborhood [Weid]

Another widely used CA are in two dimensional euclidean space using regular rectangular grid and Moore's (fig. 2.3(a), also known as 8-neighborhood) or von Neumann's (fig. 2.3(b), also known as 4-neighborhood) neighborhood. For crowd simulation it is usually Moore's neighborhood.

2.3 Cellular Automata for Crowd Simulation

Mostly when discussing Crowd Simulation and use of CA, there are properties that are similar. These are the properties:

- Space where individuals move is approximated to the plane, or positions are projected to the plane (we call this part of the plane, where are positions projected, in this work **layout**)
- Plane is divided in the regular rectangular grid, we call this division **layout**

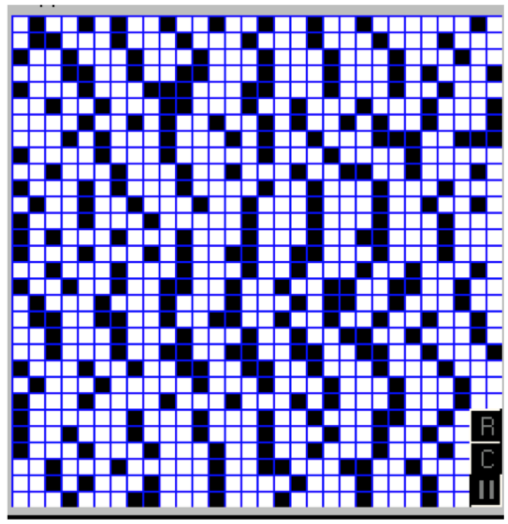


Figure 2.4: Cellular Automaton during Pedestrian Simulation [BA00]

grid.

Definition 34. Layout Grid *is a finite set of regular squared cells with following properties:*

– *All cells have the same size*

– *Intersections of the two cells either vertices, or edges*

– *Whole layout is covered with these cells*

– *There are inner cells, and outer cells, inner cells share each vertex and each edge with other cells, outer cells share at least three vertices and two edges with other cells.*

– *if two vertices are share with two cells, also edge connecting these two vertices is shared between two cells.*

- Group Member occupies one whole cell of this grid
- Size of the individual is approximated by the 0.5m x 0.5m cell and it is usually visualized by the circle that fits in this rectangle
- In most simplified versions rotation of the individual is not important

- Rules for the CA are usually more complex than in very simple version of the automaton
- Rules affect values of crowd members (velocity, direction, atd.) and these result in movement on the grid. This movement affects values in CA (for example: occupied, unoccupied)

Crowd simulations that use CA are mostly simulating pedestrians. One of the main pedestrian properties - line forming (explained in subsection 2.4) is easily done using rectangular grid, as could be seen in fig. 2.4.

2.4 Behavior Patterns

Behavior Patterns are behaviors that were found during psychological studies of crowds. Mostly they are studies of walking pedestrians and mostly they are studies of the persons without disabilities.

Flocking

Flocking Behavior is one of the lowest forms of behavioral modeling. Members only have the most primitive intelligence that tells them how to be a member of a flock [Rey87], [Par07].

Velocity of normal person

The pedestrian velocity depends on the crowd density. Kladek function describes the variation of velocity function of density. The following equation describes the Kladek function [BEHG11]

$$V_{F,hi} = V_{F,hf} * [1 - e^{(-1)*\frac{1}{D} - \frac{1}{D_{max}}}]. \tag{2.3}$$

We note that:

- $V_{F,hi}$ is the velocity of the pedestrian located in a crowd with a given density $[m/s]$

- $V_{F,hf}$ is the pedestrian velocity with free movement $[m/s]$
- D is the crowd density $[p/m^2]$
- D_{max} is the crowd density within a pedestrian stop moving

Goals of a normal Person

The goals of a normal person can be classified according to their importance. For example, *self-preservation* and the *family preservation* are usually the two most important goals for everyone. *Obstacle avoidance* is a part of self-preservation [BEHG11].

Pedestrian's preferences

A pedestrian chooses generally the fastest way to achieve his goal and tries to satisfy Law of Minimal Change and Least Effort.

Definition 35. Law of Minimal Change *is satisfied when pedestrian chooses the straightest way, with the minimum of changing direction, the most attractive and the less noisy [BEHG11]. Moreover a pedestrian typically prefers not to take detours.*

Definition 36. Least Effort (or Least Energy Consumption) *is the easiest path or route from A to B that individuals take as they progress through an environment. This can be reduced to two simple algorithmic rules [Sti00].*

1. *Individuals will take the shortest available route to get from source to destination.*
2. *Individuals try to move at their normal speed.*

There are also other pedestrian's preferences.

- He/she do not choose to move in the opposing direction to the main crowd flow, even if the direct way subsequently chosen is crowded.
- They choose the most familiar one and the easiest to achieve their goals.

- In order to avoid collisions, pedestrians try to keep a certain distance from other members of the crowd and from obstacles. This distance decreases if the pedestrian is in a hurry or if crowd density increases [BEHG11].

As a result of the pedestrian's preferences mention above, in dense crowd, pedestrians usually try to form bi-directional lines on the pathways to satisfy least energy consumption. It depends on the cultural preferences if this lanes are right or left oriented.

3

Related Work

In the previous chapter 2 we explained basic definitions and terms used in the crowd simulation terminology. In this section we would like to discuss different methods used for the crowd simulation either using cellular automata or in general. Firstly, we explain basic methods that are used for these problems and that are core for the modern approaches.

3.1 Classic methods

Behavioral animation is a hot topic in computer graphics since 1985, when SIGGRAPH video Eurythmy was presented [AGK85]. In this video group of flying virtual living beings is simulated with the behavior present. Moreover in 1987, Reynolds published the most cited paper in the field of behavioral animation [Rey87]. In the next paragraphs we refer to this article. He introduced the concept of a simulated birds, or boids (see definition in section 2.1.1) and also a flock, that is created from finite set of discrete boids. To simulate a flock they simulate the behavior of an individual bird and allow them to interact according to the behavioral patterns.

Each simulated bird is implemented as an independent actor that navigates according to its local perception of the dynamic environment, the laws of simulated physics that rule its motion, and a set of behaviors programmed into it by the "animator". The aggregate motion that we intuitively recognize as **"flocking"** (or schooling or herding) depends upon a limited localized view of the world. Not only is it unrealistic to give each simulated boid perfect and complete information about the world, it is just plain wrong and leads to obvious failure of the behavioral model.

Flock motion must be merely the aggregate result of the action of individual animals, each acting solely on the bases of its own local perception of the world. Natural flocks seems to consist of two balanced, opposing behaviors: a desire to stay close to the flock and desire to avoid collisions within the flock. The basic urge to join a flock seems to be the result of evolutionary pressure from several factors: protection from predators, statically improving survival of the (shared) gene pool from attacks from predators, profiting from a larger effective search pattern in the quest for food and advantages for social and matting activities. A bird might be aware of three categories: itself, its two or three nearest neighbors, and the rest of the flock.

3.1.1 Flocking behavior

Flocking behavior simulation leads to these subproblems:

- **collision avoidance** avoid collision with nearby flockmates
- **velocity matching** attempt to match velocity with nearby flockmates, where velocity is a vector quantity, referring to the combination of heading and speed
- **flock centering** attempt to stay close to nearby flockmates, because each boid has a localized perception of the world, "center of flock" actually means the center of the nearby flockmates

It is simple in concept yet is so visually complex, it seems randomly arrayed and yet is magnificently synchronized and overall motion seems fluid. Extension to this approach is definition of other behaviors for the flocks, such as seeking and pursuit behavior [Rey99]. This method can be used also for simulation of other living beings even for humans. On the other hand, a flock scripted in this manner would be hard to edit (for example, to alter the course of all birds for a portion of animation).

Another important method in field of behavioral animation is simulation of artificial fish [TT94], where not only flocking behavior is simulated but also physical model with muscles, water dynamics, artificial water and other properties. This method proved that behavior animation could be used also for the scenes, where complete model with motion can be successfully incorporated in the environment. Even simulation of the traffic is similar to this problem [SWML10]. Modern methods try to solve the same problem, but without all predefined variables. They try to find proper algorithms or mathematical description.

Moreover also research in a field of psychology will help to improve behavioral models for simulation. Pedestrian behavior is more in the consideration as it is goal of many modern approaches to properly simulation pedestrian movement. These simulation can be used to analyze bottlenecks in emergency routes, or could be used to populate virtual spaces. Behavioral patterns that are mostly used in these simulations are [BA00]:

- pedestrians form a directional lines
- side stepping (lane changing) instead of slowing down
- forward movement (braking, acceleration), attempting to achieve desired speed
- conflict mitigation (deadlock avoidance), finding optimal routes for the current situation

Modern methods can be divided into two groups: microscopic models and macroscopic models [SHT10]. Microscopic models simulate crowd by setting the properties of the individuals. These methods include rule-based models [DDW06] and agent-based models [Rey87], sometimes these two groups are considered as one. On the other hand, macroscopic methods simulate crowd by setting the properties of the crowd as a whole. These methods include cellular automata [BA00] and social forces [HM95]. Social Force Models are used in general in public situations, obstacle avoidance is hard as distance to obstacles must be frequently computed, but behavior control is easily done. Cellular Automata Models are criticized for lacking realism, not suited for high density crowds, but easily implemented and collision detection is not time consuming. Rule Based Models use specific finite rules for low density crowds. It produces unacceptable results for dense crowd. Agent Based Models are a collection of autonomous and intelligent agents with simple internal rules. Both of these models are good for complex behaviors and emergent phenomena. Such models can capture each persons unique situation: visibility, proximity of other pedestrians, and other local factors. On the other hand rules are difficult to develop behavioral rules that consistently produce realistic motion. Rules are based on mathematical equations [BEHG11]. Usually combination of methods is used, because microscopic models are appropriate solution for the behavior and macroscopic models are appropriate for the collision avoidance. This combination of methods can also bring some problems.

3.1.2 Social Forces

Social forces [HM95] are a measure for the internal motivation of the individuals to perform certain actions. They are analogy to fluid simulation, only here forces are not based on physical world. Social forces, such as goal, comfort and others are combined to define motion of the pedestrians. Pedestrian wants to reach a certain destination $\vec{r^0_\alpha}$ as comfortable as possible, without detours. This path could be described as polyline with the edges $\vec{r^i_\alpha}, i \in \{0, n\}$. If $\vec{r^k_\alpha}$ is the next edge of this polygon to reach, desired direction $\vec{e}_\alpha(t)$ of motion will be:

$$\vec{e}_\alpha(t) = \frac{\vec{r^k_\alpha} - \vec{r}_\alpha(t)}{\|\vec{r^k_\alpha} - \vec{r}_\alpha(t)\|} \tag{3.1}$$

where $\vec{r^t_\alpha}$ denotes the actual position of pedestrian α at time t.

Repulsion could be simulated using social forces, for example comfort. A pedestrian normally feels increasingly uncomfortable the closer he/she gets to a strange person, who may react in an aggressive way, therefore they [HM95] set ”private sphere” to each pedestrian. Moreover they define **direction depend weights** where objects and pedestrians that are in the moving direction of the pedestrian have higher weights than those that are behind [HM95].

3.2 Using Cellular Automata

As is discussed in section 2.2, Cellular Automata (CA) could be successfully used for the crowd simulation [BA00].

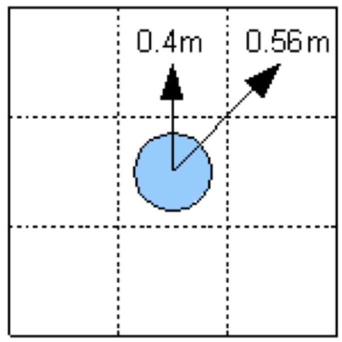


Figure 3.1: Difference of movement speed in diagonal direction and 4-neighborhood direction [SHT10]

We now explain in this section different methods how to achieve the best results. The main problems are with the behavior control and movement, as the classical definition of CA is not well suited for such complex problems as behavior, therefore extension to the definition is needed [DDW06]. And also there is a problem in the speed of movement, when using Moore's neighborhood. Speed is different when moving in the diagonal direction and in the direction of 4-neighborhood, see in fig. 3.1. We call this problem in our work **diagonal displacement**. Another problem in the movement is when cell size is that of individual and then discreet grid movement is visible.

In standard methods using CA [BA00] movement is done in discrete timesteps, where in each step movement is calculated and every participant moves at the same time. Movement is possible only to unoccupied cells. As there are different speeds, problem of crossing the same cell for more participants could occur. It could be solved with proper implementation.

3.2.1 Local Rule

In this approach authors of [DDW06] extend local rule to satisfy more realistic behavior. Firstly, we would like to define what is local rule.

Definition 37. Local Rule *assignes the next state of the cell depending on the state of the cell itself and the state of the cells in neighborhood [DDW06].*

Extension of this local rule is in the cells that are affected by the decision process. In this extension not only state of the cell itself is affected but also selected cells from the neighborhood. On the other hand, not only cell and the neighborhood cells define rules for the next state, but also other selected cells. Appropriate decision of the selected cells affect whole decision process and is core to this approach. For example, let environment be hall with exits, such as cinema hall and people are leaving through these exits. Then selected cells are also cells around the exits to avoid traffic jams in pedestrian traffic. There are also specific cost function defined to have better decision process [DDW06].

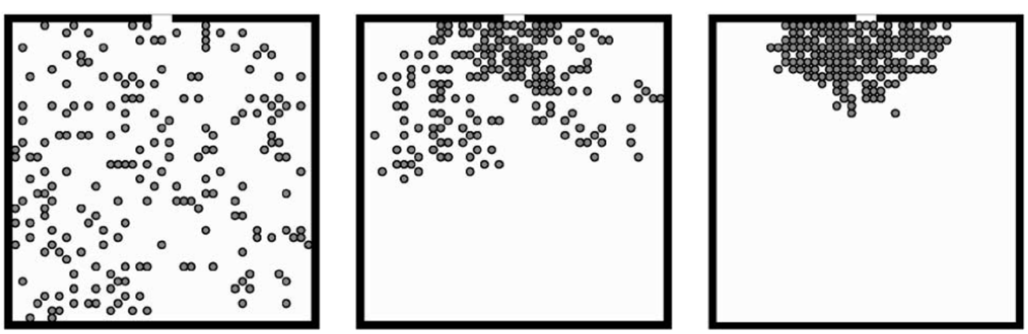
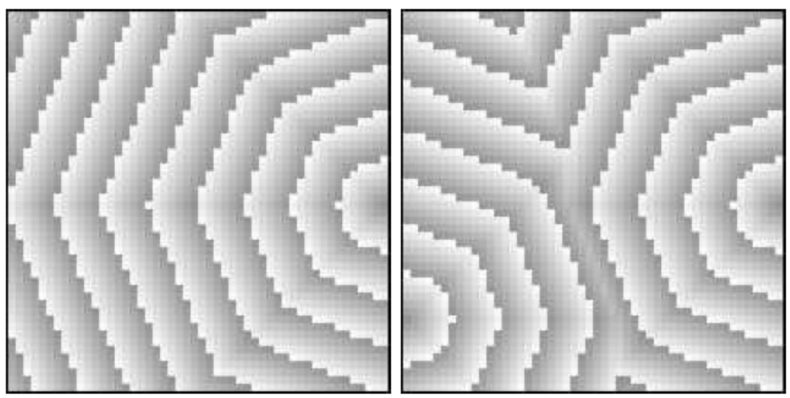


Figure 3.2: People leaving a room with one door only [BKSZ01].

3.2.2 Floor Field

This approach is used for simulation of pedestrian traffic and CA is used to capture dynamics of this traffic. To reproduce certain collective phenomena **floor field** is used. It is necessary to use this or other similar method to produce long-range interactions, such as interaction between pedestrians and geometry of the building. There are two possibilities of the floor field, first is static, which does not evolve in time and examples are walls, and emergency exits. Secondly it is dynamic field, that is modified by the presence of pedestrians. This field is usually used to model a long-ranged interaction. Example of this interaction can be a trace, that leave every pedestrian as their position changes. Both these floor fields are implemented as another special layout grid. When floor field enhancement to the standard CA is used this affects the pedestrian's desire and state. Specially in emergency situations, when pedestrians can leave track, others can follow them and easily find way out. On the other hand also pedestrian flow and line forming behavior could be successfully captured by floor field method. Example in fig. 3.2 shows evacuation of large room [BKSZ01].



(a) (b)

Figure 3.3: Here we see the rings of equal value (distance) propagating out from the source in (a), and how well Potential Fields apply to multiple exits (b). The lines represent contour information [LM03].

3.2.3 Potential Fields

There are many application of pedestrian simulation where flow of people through environment is needed to visualize. Therefore there must be some technique that determines direction of this flow. **Potential fields** provide a means of extracting global routing knowledge, which is necessary for the flow. For every position in the environment there is a direction that provides the shortest route to the exit. A Potential Field is generated from the exit points and the shortest exit route found by choosing the direction from a pedestrian cell that has the lowest value on the Potential Field, see fig. 3.3. Simple approach of generating such a field involves each cell recursively applying its incremental count to all adjacent cells in 4-neighborhood and $\sqrt{2}$ to all diagonal cells. This recursion starts at exits. It is approximation of the shortest Euclidean distance. Extension to this approach are dynamic potential fields, when goal is changing it's position [TCP06]. It is very powerful technique also because of the obstacle avoidance, where cells containing obstacle will not apply incremental count to the neighbors [LM03].

3.2.4 Least Effort

Least Effort is an approach that has various implementations with various enhancements, but the general definition is explained in section 2.4. This main idea is in many variations used in [Sti00], [SHT10], [SHT09] and others. According to the definition Least Effort approach finds optimal path to achieve a goal for pedestrian. Depending on the actual algorithm, this least effort is achieved differently. One of the implementation uses basic approach and enhances it to satisfy requirements pedestrians, that move in a group [SHT09]. They use probability model, where more probable are cells from Moore's neighborhood that are closer to the goal. This model is then enhanced to produce movement of the group where members of the group try to keep short distance with the others. To achieve this behavior, they proposed a least effort equations for the followers of the leader in a group to gather close distance for the members in a group, more details are in the paper [SHT09].

3.2.5 Fine Grid

This method of using fine grid cellular automata solves problem of unrealistic movement along the grid. They solve the problem by dividing space into grid with smaller

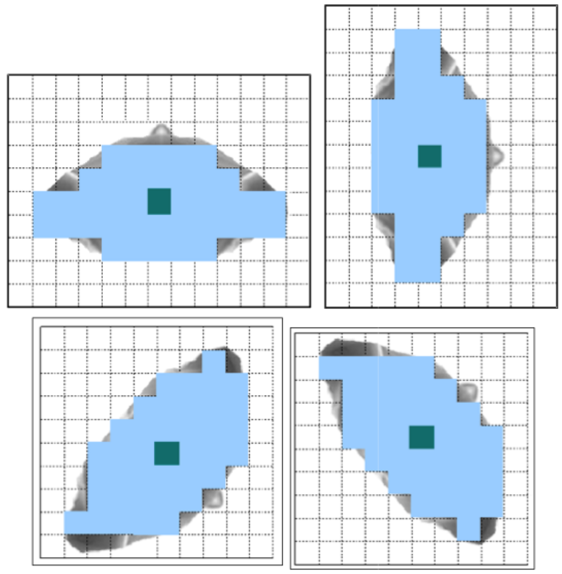


Figure 3.4: Representation of a pedestrian and approximation in fine grid cellular automata with different orientations [SHT10]

cells than 0.5m x 0.5m as it was in classical approaches. This division to smaller cells brings also problems with visualization and rotation of pedestrians. Here orientation is important, because different cells are occupied in various angles, as illustrated in fig. 3.4. When a person is represented only by one cell, orientation is not that important. They applied this approach in emergency simulations, but it could be used also for another crowd simulation problems.

For the problem of optimal path finding they use *Least Effort Algorithm*. This algorithm finds optimal path to the goal position by calculating probable movement to the next cell in the Moore's neighborhood and distance to the goal. Moreover, they also tried to solve problem of diagonal displacement with set of constraints when moving in the diagonal direction.

3.2.6 Conclusion

Cellular automata is suitable approach for easy and efficient collision detection and emergent behavior in low density situations. On the other hand, movement and realistic behavior of a crowd is a problem. Methods mentioned above improve solutions for these problems, but CA are still not suitable for high density situations. Movement using Fine Grids is better, than classic approach, but still discrete movement is visible (much less than in standard methods). Behavioral control has improved using Potential Fields and Least Effort methods, but still collective behavior of smaller groups is not sufficiently solved. Grid based approach as CA is, is suitable for information about environment using similar methods as Floor Field.

3.3 Crowd Simulation

In this section we would like to present various problems and methods that are connected to the crowd simulation, but usually are not that concerned with the psychology as this is discussed in the next section 3.4. There are various steps when creating crowd simulation and there are problems in each of the steps. These steps include [TM07]:

- Initialization of a Crowd
- Animation and Motion
- Behavior
- Environment
- Rendering

We mainly focus in this work on Behavior, but also other problems are interesting, we briefly mention these methods in this section. For more detailed explanation refer to the source. Firstly the crowd must be initialized and there are different options how to solve this problem. To create a crowd we need to choose and set a density of members. Than we can choose positions and set personal preferences an initial values. To set these values for participants, initial values such as position, velocity, radius are centered at the actor's face [RD05a], [BA00] . These properties are part of the agent's external state and can be observed by others [GBLM10]. When modeling behavior during the simulation also perception, motor systems [TT94], [KZ11], [SMK05] and an illusion of own will [TMK00], are set. Moreover also list of goals and interests, emotional states among others, level of relationships, level of dominance are personal values, that help to define behavior and are set before actual simulation [MT97].

3.3.1 Motion Graph

Motion Graph is the graph structure, that is used to the creating new motions from existing. Motions are from MoCap data, but could also be from manually defined data and this structure creates better usage of this data. Motion graphs transform the motion synthesis problem into one of selecting sequences of nodes, or graph walks.

Definition 38. The Motion Graph *is a directed graph wherein edges contain either pieces of original motion data or automatically generated transitions [KGP02].*

Motion Graph is technique that could be also used for the motion retargeting problem, where data usually from Motion Capture are mapped to the new characters [Gle98], [Fra11]. New characters usually do not have same geometry as the source ones and during retargeting it is necessary to keep main motion characteristics. When this retargeting is between models with different topology this problem is even harder.

3.3.2 Group Motion Graph

Group Motion Graph is another graph structure, that is used in crowd simulation and preserve spectral relationships between members of the crowd. It allows interactively manipulate motion of the crowd. The graph is created in a way, that each vertex represents the location of an individual at a sampled frame, edges represent moving trajectories and neighborhood formations as shown in fig. 3.5. Moreover, once a graph is created a user can manipulate vertices and by them also the whole group. Therefore graphs can be stitched together and longer motion can be achieved. Furthermore, using this motion graphs also efficient collision detection can be calculated similarly to approach proposed in [SKG05]. The key positions of individuals and poses are

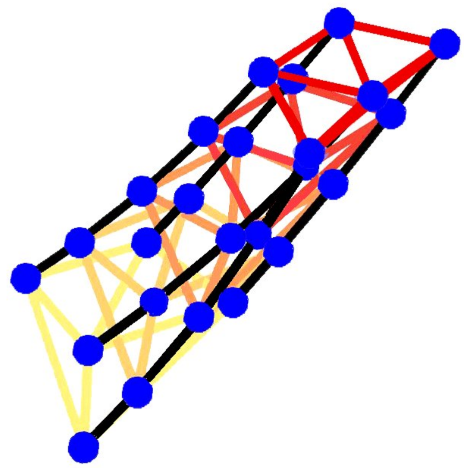


Figure 3.5: A group motion graph [LCF05]. A group motion graph constructed from the clip. Vertices (blue dots) are connected in two sets of edges, formation edges (colored edges in the figure) and motion edges (black edges).

defined and then the optimal path is found. At first, probabilistic roadmaps are created for navigation and path planner. Afterward the randomized search algorithm is created for refinement.

In a method by Kwon et al. [KLLT08] the motion graph is enhanced to provide multiple motion clips in the same timeline. Either larger groups can be divided into smaller or groups can be combined together and form larger formation. In graph the edges are divided into formation and motion edges. Formation edge represents neighborhood relationship between vertices and can be useful to preserve adjacent relationship. However, these relations are usually not well defined. Formation edges define movement in the space and motion edges define movement in the time. For spatial features the whole group needs to be considered to compute movement, but for temporal features only moving paths of individuals are considered. Spatial movement is calculated for the keyframe. Both these edges together define spatiotemporal movement of a participant.

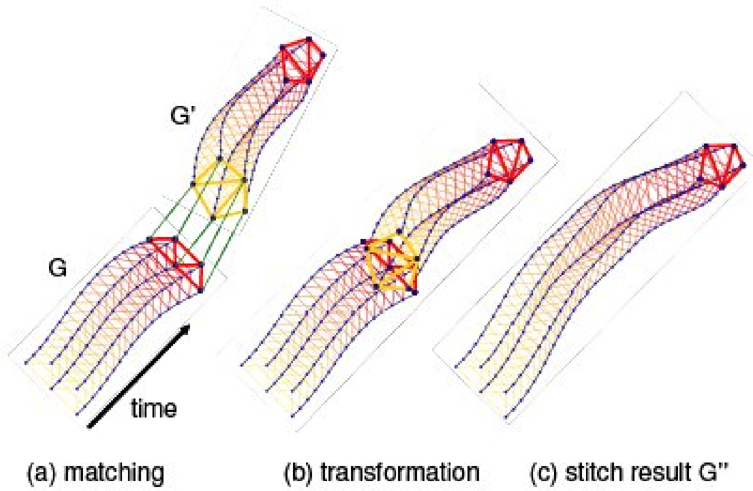


Figure 3.6: Group motion stitching steps.
(a) finding corresponding points (b) aligning of the graphs (c) smooth blending between the graphs [KLLT08]

3.3.3 Group Formation Control

Crowd animation is used not only to model behavior and test various risky scenarios, but also to bring visually interesting scene. These scenes are used in the motion movies, where groups of creatures are very popular in the recent years [Ker05]. These groups are visually interesting not only because of the individual behavior, but also their movement and positions can create pleasant, attractive scenes.

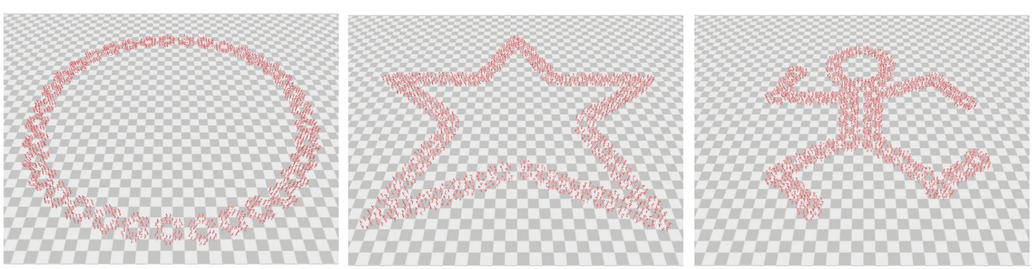


Figure 3.7: Formations created by positioning performer [TYK+09]

Group formations in the real world situations can be found in the mass performances or tactical sports such as soccer. This situations have inspired scientists [TYK+09] to provide a mathematical description of the motion. This model allows to compute the smooth and realistic movement of a group while respecting adjacency relationships. In mass performances relative positions between neighbors are usually kept to achieve visually pleasant movements.

Firstly, they extract positions in the formation from a captured video. Adjacency relationships are extracted from the formation with Delaunay triangulation and Motion Graph is created. Usually a scenario and spatiotemporal correspondence is provided beforehand by an artist or a choreographer by defining the shapes or even position of individuals. Afterward automatic calculation of smooth simulation is possible using extended Catmull-Rom splines.

Collision detection is solved in post processing because only when linear trajectory of a point is inside the obstacle, this trajectory is adjusted by moving the deepest point from collision to the boundary. This process is iterative and continues until trajectory does not penetrate obstacle. In the final graph vertices represent individuals and edges are defined by the triangulation. Edges have positive weights, that are defined as the inverse of the distance between vertices. It is also use hierarchical method, where individuals are grouped in the small group and they act as one entity. More detailed information about this approach are discussed in [TYK$^+$09] and result are in fig. 3.7.

3.3.4 Shape Constrained Flock

Shape constrained flock is a flock in which positions are generated to satisfy predefined constraints. There could be different types of constraints set, one of which is shape constraint, more specifically 3D shape is set as this constraint. Moreover, this object can change it's properties during the time, either by deformation, or by movement and the flock is modified to satisfy constraints and flocking behavior.

During the simulation these steps are calculated to achieve pleasant result:

1. sample surface of large object with a set of evenly distributed sample points based on the surface mosaicing technique [LHM06]

2. establish correspondence between agents in the flock and sample points on the

Figure 3.8: Shaped created from the flock [XJY+08]

surface

3. establish correspondence in the source surface

4. simulation

Mosaicing technique assumes each flock member contains spring like energy, this energy between them gives rise to a repulsive force between neighbors whose Manhattan distance is less than A, where A is related to the number of elements N and the total surface area M as follows [XJY+08]:

$$A = k\sqrt{(\frac{M}{N})} \tag{3.2}$$

where k is 2.0 in current implementation. Spring like energy between points i and j can be defines as [XJY+08]:

$$E_{ij} = e^{\frac{-dis_{ij}^2}{2\sigma^2}} \tag{3.3}$$

where σ is the interaction radius. It is used to control the fall-off of potential energy, and does not affect the final pairwise distances in equilibrium. σ can be set as follows [XJY+08]:

$$\sigma = w\frac{M}{N} \tag{3.4}$$

They choose w as 0.9. Distance can be chosen either as Manhattan distance or Euclidean distance. Manhattan tends to produce quadrangular distribution and Euclidean tends to produce hexagonal ones. They define repulsive force by using a simplified version [XJY+08]:

$$F_i = \sum_{j \in U} norm(p_i - p_j) \times E_{ij} \tag{3.5}$$

where U is neighborhood of point i, and i does not belongs to U.

There are two of agents behavior during simulation. When agent is far from source location, then Reynold's boids behavior model is chosen [Rey87] with separation, cohesion, alignment. When agent is close to destination, additional control forces are incorporated, such as damping and homing.

When establishing correspondence between flock agents and sample points on the constraining shape a random assignment suffices in most scenarios. To achieve better temporal coherence between two overlapping constraining shapes, they obtain initial correspondences by spherically projecting source positions on the first shape onto the surface of the second shape, and let these projected points subject to energy optimization [XJY+08].

They introduced also a new steering behavior - **homing**, The homing behavior always drives an agent towards its own destination. Results of this approach are shown in fig. 3.8.

3.3.5 Collision

There are three types of approaches concerning collisions. These approaches are Collision Prediction, Collision Avoidance and Collision Detection. Also obstacle avoidance is part of these collision approaches, but it could be incorporated, when static objects from the scene are taken into account as actors without the position change. Difference between them is discussed in section 2.1.3. Mainly, they are different in how early they prevent or detect possible collisions.

Collision Detection is a method of finding, if two actors collide when heading to the same position. Relative position of two actors after t frames are [RD05a]:

$$p(t) = p(0) + \vec{v}.t, \tag{3.6}$$

where t are frames, $p(t)$ is relative position after t frames, $p(0)$ is initial position, $\vec{v}$ is relative velocity. Distance between them $d(t)$ can be found using [RD05a]:

$$|d(t)|^2 = |d(0)|^2 + 2t(\vec{v}.d(0)) + t^2|\vec{v}|^2. \tag{3.7}$$

Collision will occur, when this distance is less than twice the radius (r) of an actor. Therefore the whole equation for the collision is [RD05a] :

$$|d(0)|^2 + 2t(\vec{v}.d(0)) + t^2|\vec{v}|^2 = (2r)^2 \tag{3.8}$$

There are different **types of collisions**, depending on the type and they have to be solved differently. They are mostly:

- **towards** - they have almost the opposite direction, which means $\vec{v_1} \circ \vec{v_2} < 0$, where $\vec{v_1}$ and $\vec{v_2}$ are oriented vectors with direction of movement and length of speed for first and second actor respectively and $\circ$ is dot product.
- **away** - they have almost the same direction, different velocities, faster is behind
- **glancing** - they are near each other, have crossing direction

To find out, which type of collision will occur, we can simple calculate direction (towards is find out), then find a vector that is perpendicular to the line that is defined by the positions of the two actors, and find out in which halfplane are direction vectors of the actors. If there is the same halfplane for both direction vectors, then it is an away type, else it is a glancing type [RD05b].

Collision Prediction is a type of approach, where actors try to predict collisions before they actually can happen. They usually use well defined extended visual system to better understand the knowledge of position of the others. There are different approaches to solve this problem. One of them stores a list of predicted collisions with in the time until they occur, based on the predicted paths on which actors will move according to their actual preferences [RD05a]. They also define 30m as a maximum distance at which collision could occur [RD05a].

Collision Avoidance is a method how to solve predicted, or detected possible collision. It is a method how to avoid them. There are different approaches how to solve this problem, usually they combine psychology with numerical methods. Basically, there occur three simple collision avoidance behaviors, which have to be solved differently. These behaviors are [RD05a]:

- changing **direction only** - try detour according to shoulder overlapping, try 6 different directions (tested for collision with actual collide or nearby actors)
- changing **velocity only** - speed change 50%, slower/faster
- changing **both**

Which of them is selected depends on the personal preferences and behavior of the actor [TCP06], for example if actor is in hurry, will not slow down, firstly tries detour, if detour is not possible, than he/she will temporarily slow down [RD05a]. Extension of choose the right collision behavior is adding knowledge of the neighborhood to the personal preferences. One of the methods is based on the collision type. If it is a glancing collision, temporarily slower the slow actor, if they have equal velocity then choose randomly. If it is towards collision type than change direction [MT97]. Other velocity-based approach chooses velocity of an agent from two-dimensional "velocity space" in which certain regions are marked as forbidden because of the presence of the other agents [GBLM10].

Other division of the avoidance behavior is [SMK05]:

- **urgent avoidance** rapidly decelerate or sharply veer by side stepping
- **smooth avoidance** gradually steer to the sides when they have enough time

Where smooth avoidance uses predicted model of the actor's paths, urgent reacts to the neighborhood that was changed immediately. Smooth avoidance can reflect personal preferences and behavior.

3.3.6 Conclusion

There are different problems in crowd simulation not only with behavior and collision detection but also with movement of individuals, creating heterogeneous crowd [TM07] and others. For the movement Motion Graph method is powerful approach to find new motions and retarget them to new characters. Also shapes created from the members of a crowd are very visually interesting and useful specially for motion pictures. However these methods are very interesting, we are more concerned in this work on behavioral control and collision avoidance as these two problems are connected.

3.4 Behavioral Animation

Behavioral animation is a set of animation methods that are not based on the geometrical transformations, but on the change in behavioral properties. Objects itself usually approximate some living beings and also behave in the same manner. If pure behavioral animation is in concern, objects are easily approximated and visualized as simple spheres, or circles, geometry is not important. Important is the change in position, other movement properties and behavioral properties.

Behavioral animation and simulation based on behavior are closely connected to the collision prediction/detection/avoidance, because way the objects find new position is based on they preferences (which is behavior) and based on their options (which is collision detection).

In this section, we will use term **object** or **actor** as member of the crowd.

3.4.1 Perception Model

For the behavioral animation it is necessary to have an optimal model of behavior, but also to have proper input variables. These input variables are usually provided by the sensing system. Virtual sensing system of the members is usually constrained and actual result depends on the right choice of these constraints. There are different approaches to this problem solution.

Usually, human sensing system is constrained to only visual information, than it is called visual system and collision detection is highly depending on optimal settings of this system. Variables from visual system include Field of View (FOV), height of the person (heigh from which other objects are observed), refresh rate, sometimes memory and others.

Field of View is usually taken within 60 degrees horizontally either side of the direction [RD05a]. Others claim, that horizontal perception field is divided into three main parts. The first part is defined by a vision angle of 30 degree. In this field a human can see object in detail, in vision angle of 100 degrees can see only object forms, in 200 degrees only movements of objects are seen [BEHG11]. Moreover, within the human eye there is a small region known as the **fovea**, which extends over a visual angle of 2°. This is the main region used to make detailed observations of the world: the rest of the eye provides peripheral vision, with only 15-50% of the acuity of the fovea [RD05b]. We can use this information to have four different rendering techniques for four different levels of detail, depending in which region they are.

Psychological virtual memory is part of the sensing system, that helps actor understand the sensed stimulus from the previous actions. Each pedestrian reacts to observed environments, and the behavior is modeled as individual and independent intellectual entity, which is called pedestrian agent or simply agent [SMK05]. Another part is **visual sensor** that obtains information about environment, detects position and speed of other agents within the visual range and fails to sense when interrupted by obstacles.

Others extend visual system by other senses, such as touch and sound. In particular, the sound sensor is useful for detecting agents approaching from behind or around the corner, which would otherwise be invisible to the agent. Moreover the agent's attention components are introduced to model a pedestrian's attention system. Pedestrians are not expected to notice everything that they sense in the environment, that is an object in the environment may been seen but not se consciously processed by a pedestrian if he/she is occupied by other objects [KZ11].

Usually these methods with perception employ **perception-reaction model**. In this model behavior is a reaction to the perceived environment according to the theory of social psychology [SMK05].

3.4.2 Model of Emotions based on Psychology

For virtual crowds, we have to simulate behavior, because real human beings express feelings and emotions. That, among others, separates us from non-living things. Also virtual characters have and express emotional states, to form context-specific emotional memories and for learning. To be more precise, our actions are compound of action itself, a trigger context (when the action take place), a stopper context (when the action ends), an object to which the action will happen. These four variables form **Action Tuple** [TB01]. According to the **Thorndike's Law of Effect** [TB11] actions that correlats with positive results will be chosen more frequently in the future.

Basically there are two main approaches to define emotions according to the psychology. The first one is a categorical approach, separates emotions in a basic set of emotions (fear, anger, sadness...), it is more discreet approach. Secondly, there is dimensional approach, that better applicable for more complicated situations, such as behavior of a crowd in a museum. In this approach, emotions are mapped onto a real axis, mostly 3-dimensions are used. According to the psychology three axis are used: Pleasure-Arousal-Dominance. Emotional states are then defined as 3 dimensional vector. This vector can be mapped to the categorical approach as categories. Moreover psychological studies found out, that not only sensed memory is important for the correct behavior, but also Context Specific Emotional Memories (CSEM's) that are remembered with the specific situation [TB01].

3.4.3 Modeling Behavior

There are different approaches how to build group behavior. According to the Reynolds [Rey87] behavior of a group should be built up from the action of all its members and create flocking behavior and others. According to the Still [Sti00] crowd should be simulated as emergent behavior, from the view of individuals.

When discussing behavior, we need to model mental states that in a whole creates behavior. Mental states are different for the type of the actors, when they are artificial fish, their mental states are hunger, libido, fear from the classical approach [TT94]. This states change in time according to the personal preferences and memory (when was the last food, appetite, etc.) Their change is based on the intension, incrementally tries to fulfill fish's intention. This method is defined as:

Definition 39. Persistence of Intention *is preventing suddenly changing the goals [TT94].*

Persistence of intention is supported also by the storing previous intention when changing to the new one. This will allow actor to return back to the previous goal, for example, when direction is temporarily changed, actor can come back to the previous direction after detour. Intentions are personal preferences, different from the goal driven methods. On the other hand, intentions also define a goal and also other way around. Goal does not have to be a static location, that actors try to achieve, it could be dynamic goal, for example chasing someone [TCP06].

From the psychology, there is a hypothesis, that [TCP06] :

- Each person is trying to reach a geographic goal
- People move at the maximum speed possible
- There exists a discomfort field g so that, all things being equal, people would prefer to be at point x rather than x' if $g(x') > g(x)$
- People choose paths so as to minimize a linear combination of the following three terms:
  - The length of the path
  - The amount of time to reach the destination
  - The discomfort felt, per unit time,along the path.

Actors also try to minimize their discomfort, that could be caused by the high density of other actors in the neighborhood. According to the psychological models discomfort occur when neighboring agents impose mental stress on each other, mental stress increases exponentially as others get close, and it becomes critical at certain distance. There are different regions for the different levels of stress [SMK05]:

- **cautionary region** - outer radius, gradually steering to the sides without deceleration
- **critical region** - inner radius, where the agent takes immediate action to avoid collision

Moreover, density could be defined in crowd density field and evaluated for every timestep and every crowd member [TCP06]. These hypothesis above needs to be divided in the steps that define base of the simulation algorithm. These steps according to Thalmann are [TMK00], [TM07] :

- for each object and actor perception
- for each actor emotions generation
- for each object and actor behavior execution

- for each object and actor actions execution

These steps are repeatedly performed based on the behavioral mechanism that is used. This algorithm, when implemented correctly can incorporate powerful use of parallel calculation on GPU into the system.

Definition 40. Crowd Density Field *has highest values where are the actors, and falls off radially.*

This field is then used for the cost function, that is minimized and next positions are found for the actors. More details in [TCP06].

Moreover, when behavior of individuals in a group is well defined, with user interaction also relationships to the different groups could be defined. Then there are three different behaviors: move, avoid collisions and with this extension also relationship behavior. This approach is more concerned to the group behavior as a whole not only as a set of individuals in the same environment. These relationships could be defined similarly to the human relationships. Individuals then can react and behave according to their relationship to the group and create flocks (flocking behavior - see section 2.4). This could be visualized using sociogram [MT97].

Definition 41. Sociogram *is sociological graphic representing one population, its relationships and levels of dominantion [MT97].*

Behavior of the group is not only controlled by the relationships among the participants, but also with relationship between the groups. When one of the groups leads the other group, than it is higher abstraction as is in the leadership behavior of the actors, see section 3.1. Another type of relationship between the groups could be a constrain. This means that one group constrains motion of the other group. Example of this constrained behavior is shepherding with multiple shepherds [LRMA05]. Sheep communicate with each other, there is also relationship defined. They define one group, another group are shepherds. These shepherds also communicate with each other and also have defined behavior. Moreover, group of shepherds influences movement of the sheep. Therefore motion of one group is here controlled by another group. Shepherds are agents that influence the movement of a flock, where flock is a group of agents that move in coordinated manner and respond to the external factors. Goal of the shepherds is to steer the flock toward specified position [LRMA05].

3.4.4 Conclusion

Behavior control is connected with the optimal perception model and sensory system. Interesting are not only possibilities, but also right constraints. It is necessary to choose right situation and try to choose optimal behavioral patterns. There are already situations, that are highly discussed and results are almost sufficient from the behavioral point of view, such as walking pedestrians, of flying birds. Others only for very specific conditions, such as pack of wolves. Our work is more concerned by populating virtual space and find behavior patterns for exhibition hall, or museum environment [RSS+28]. Emotions as part of the behavior are very interesting, but are not well defined, therefore they are also not solved sufficiently.

4

Proposed Solutions

In this chapter we would like to explain our solutions using cellular automata for the three different problems. The first one is movement control for the group members in the dance formation. The second one is crowd control in flashmob-like situation and the third one is behavioral crowd simulation in the exhibition environment.

4.1 Motion control in a group

In this section, we suggest a new way of motion control over the individuals in a group. Our method is novel in use of cellular automaton (CA), which has been previously used only to control behavior, not motion itself. As cellular automaton we choose Conway's Game of Life [CGB82], [Weib] (GoL), because it is both simple and well defined.

We map cells from CA to the individuals in a group and values from CA to the set of moves from motion database. This mapping allows us to automatically define motion of individuals and CA gives us control over this movement. Moreover, also some extensions are proposed, that could control this mapping and bring more advanced animation. We also show some of the results and discuss problems that are left for the future work.

4.1.1 Mapping

Firstly, we define mapping between motions of a structure and CA. For our purposes motions of one figure are pre-defined and stored in the database, then some of them are chosen. Which one to choose is decided by the properties of motion - depending on what the topology of characters is, what kind of motion and what diversity of a group is needed. For the simple mapping we choose 9 motions with the same beginning and ending transformations. This way we could use any permutations of them. Number 9 given by GoL, where the future state of each cell is calculated depending on the 3x3 Moore neighborhood. On the other hand, in GoL there are only four rules, but these are also calculated depending on the same neighborhood. Therefore number of neighbors is already known in the processing pipeline.

We map every figure to some cell in CA, the easiest case is one-to-one mapping. Because there is no restriction for the grid dimensions in CA, we could use as many figures as needed. We let CA change as regular GoL and when it is changed also motions are set to the new ones with respect to the neighborhoods of the cell in the CA.

There are extensions of this simple approach. One of them change the mapping, where number of neighbors is not mapped to the motion itself, but to the speed of the motion. Here we do not use just some permutation of the speeds to assign numbers, we need to order them by the speed rate and change to next, or previous one. So the change between various speeds is smooth. With this extension we could easily map many motions - with the same transformations but different speeds.

Another extension is hierarchical mapping between individuals and CA. Hierarchy can be in the group of individuals, where more than one is mapped to one cell in CA. In this case whole group will move with the same transformations. When we also position these individuals into a small space range, they will create motion which is common in dance formations, where more dancers repeat the same moves.

Moreover, also hierarchy in CA can be used. We can have more CA link together to form balanced binary tree to create hierarchy. We then map individuals to the cell in the leaves of the tree. When going higher in the structure of the tree we could add number of neighbors from the higher CA in nonary (base-9) numeral system. Then we could have up to 9^h ($h = \textit{height of the binary tree}$) values which we could assign to the motions.

4.1.2 Group Motion

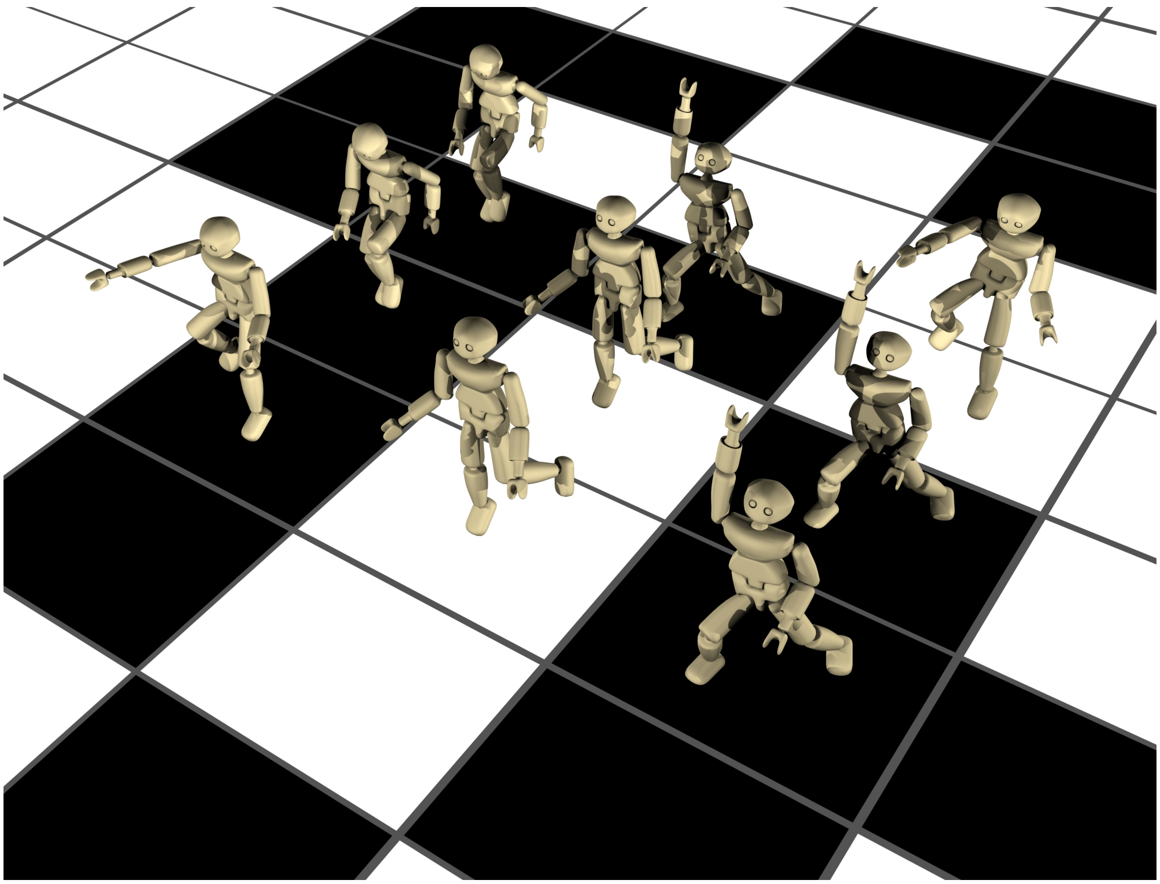


Figure 4.1: Cellular automaton cells are mapped on the floor grid. Black cells are occupied, white are empty. Movements of robots are according to the number of neighbors.

As discussed in previous section 4.1.1, we map individuals from a group to the cell in CA. Sum of neighborhoods is a value obtained from the cell and it decides which motion from the selected set is used, as it can be seen in Fig. 4.1. Initial setting for the CA is used for the first move. Currently, for initial setting, simple binary white noise is used to identify cells which are occupied and which are not. Following moves are calculated from the values of associated cell to the figure. As transformations for the beginning and end of motions are same as well as length of motion (which can be enhanced with the slower or faster settings for the move), following moves are seamless, without any discontinuity of given function, the only problem could be derivations in the motion curves at that point. We leave this for future work, where we would like to solve also problem with various moves to avoid restriction of the same transformation for the beginning and end of motion. With solving this problem we would smoothly join two following moves.

GoL final state could be terminal, where neighborhood is empty for all next steps, or stable, where the neighborhood of a cell is not changed in the next steps or repeating state, where some number of neighborhood states is repeated in all next steps. If all values are mapped to some motions, animation will be infinite. Therefore we stop animation after some number of steps, or after some time. Our intention of our method was to automate some step in animation pipeline and usually there is defined a finite length for the animation.

4.1.3 Future Work

In the future we would like to define such rules for the CA, that would better control movement and preserve relationship between other participants. Another problem we deal with is motion retargeting [Fra11], specific for the group animation. We have shown some results in the above figures, but significant improvement is still needed. Therefore it is possible to use CA for the group motion control, but assumptions still need further research for the improvements.

4.2 Flash Mob Like Crowd Motion Control

This paper presents an approach for a motion control in a group. We use cellular automaton for this control and present situation where it could be shown. For our purpose we have chosen Flash Mob situation, which is a novel phenomenon of the 21st century [Dur06].

Definition 42. Flash Mob *according to the MacmillanDictionary* [1] *is: to suddenly gather in a public place, do something for a short time, and quickly go away again.*

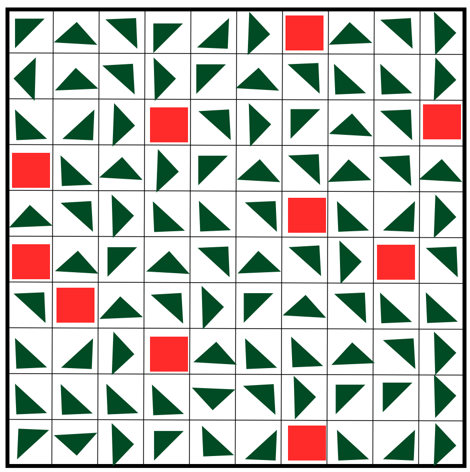
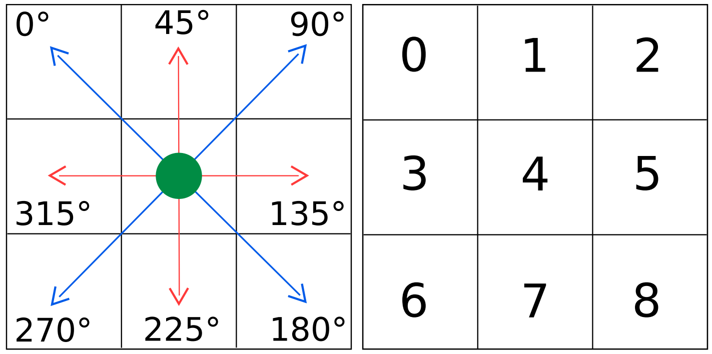


Figure 4.2: Initial step where seeds are set (in red) and random orientation to the rest of the group.

We refer to the Flash Mob *situation where group of informed people suddenly gather in the public space and start to move evenly. Rest of the group starts to move same way after some time. Movement of an individual depend on the surrounding people. Principles of social networking include behavior of an individual affected by the group and this principle is also used in Flash mob situation.*

Moreover we need to create database of the motions and define them manually. Afterwards we could join different motions to create one longer. Smooth motion is left to the future work. By now, motions need to start and end in the same pose so there are no jumps in the spatial properties of the motion, but still could be in the temporal.

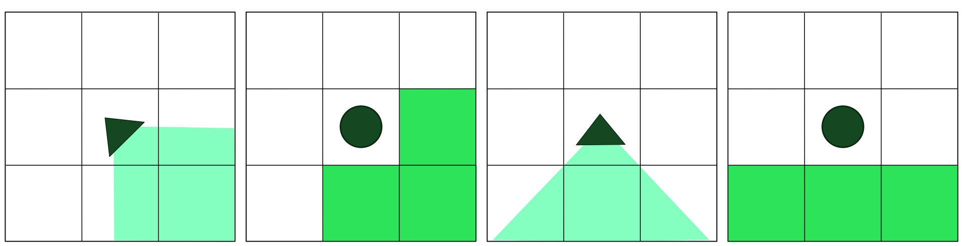
[1] http://www.macmillandictionary.com/



(a) (b)

Figure 4.3: (a) Mapping of the rotation to the polar coordinates. Angles are shown, length is set to 1. (b) Mapping to the array to easier get indices.

To use cellular automaton as a control for the group we associated cells of an automaton to the individuals in a way that state of the cell is mapped to the motion. Position of an individual in the space does not need to be same as in the automaton, but spatial relationship of the cells and position in the 3D space need to be the same. If this condition is not satisfied relationships are omitted and whole behavior and motion will not be Flash Mob-like.



(a) (b) (c) (d)

Figure 4.4: (a) field of view for the first group (b) neighborhood that is analyzed (c) filed of view for the second group (d) neighborhood that is analyzed.

4.2.1 Method

At first, there are some seeds - cells that are occupied by the informed person, that will move alike. Other cells has some random state - this means that these individuals

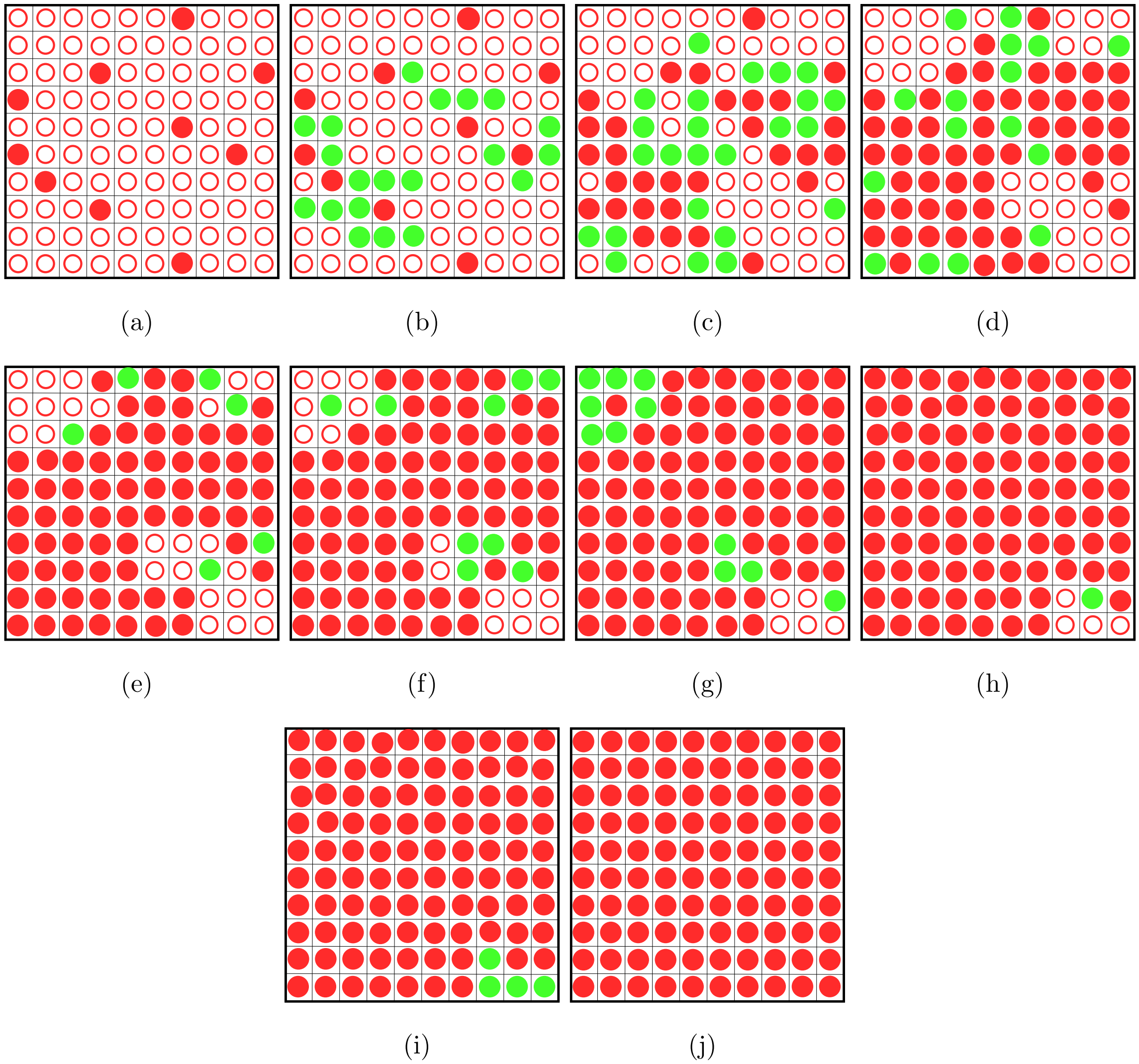


Figure 4.5: Discreet steps of the algorithm.

move with another motion and look in other direction. In this step not only states of the cells are set, but also orientation to the individuals, as is shown in fig. 4.2. Informed cells are oriented in the same direction, to create uniform motion. Uninformed cells rotate in random manner, where angular arc length is set to 1. These angles from the polar coordinates are rounded to the multiple of number 45. This way we achieve only 8 values, which are divided by 45 and we gather values from 0 to 7. This is shown in fig. 4.3(a). These 8 values are then mapped as is shown in 4.3(b) to easier access array of values in each step. Access to the array is then:

$$[i - 1 + x, j - 1 + y], \tag{4.1}$$

where i, j are indices of the current cell position in the array, x is value in the cell divided by 3, y is value modulo 3.

In each other stage we calculate number of informed cells in Moore's neighborhood that are in the Field Of View (this depends on the orientation). As there are only 8 rotations (discussed above), we can divide them in two groups - multiplies of 90 degrees is one group (shown in fig. 4.3(a) in blue), and inbetweens are second group (shown in fig. 4.3(a) in red). Field of view for these groups is set as shown in fig. 4.4(a), 4.4(c). Neighborhood is then set as shown in fig. 4.4(b), 4.4(d). If there is one informed in the neighborhood, then in the next step, cell is changed to the informed. If there are enough informed cells, after some time whole group will be informed. Process of the algorithm is shown in fig. 4.5 The exact number needed for the believable behavior is left for the further discussion, as it is the lowest number needed for the control that will lead to only informed cells.

4.3 Crowd Simulation in an Exhibition Environment

We introduce a novel grid based method of presenting participants in a crowd. We propose a psychological approach in the special case scenario in the exhibition environment. The idea enables to solve the problem of behavioral control of a group in this special case. We extend the pedestrians movement methods with our novel behavior model for the setup. We also combine various grid-based techniques to achieve possibly better performance and control.

There are several assumptions in our solution. Our environment is very specific, it is a exhibition hall, with entrances, interesting objects, without narrow corridors and crowd is not dense. Also model of the floor of the hall is a finite part of Euclidean plane, divided into the regular grid. Because of these assumptions, we benefit from grid-based approaches, with no need to deal with a dense crowd. This allows us to simplify work with collisions and also with behavior, because neighborhood is well defined and easily found.

4.3.1 Spatial Relations

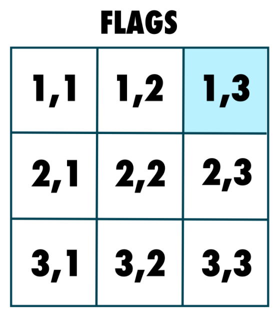


Figure 4.6: Flags used for the coordinates of an individual.

Our crowd moves on the two dimensional plane and this plane is divided into regular cells of rectangular shape. We have chosen rectangular cells for their simplicity, but there are other polygonal regular grid, that might be more suitable for our problem. We postpone this discussion in the future work considerations, section 4.3.4.

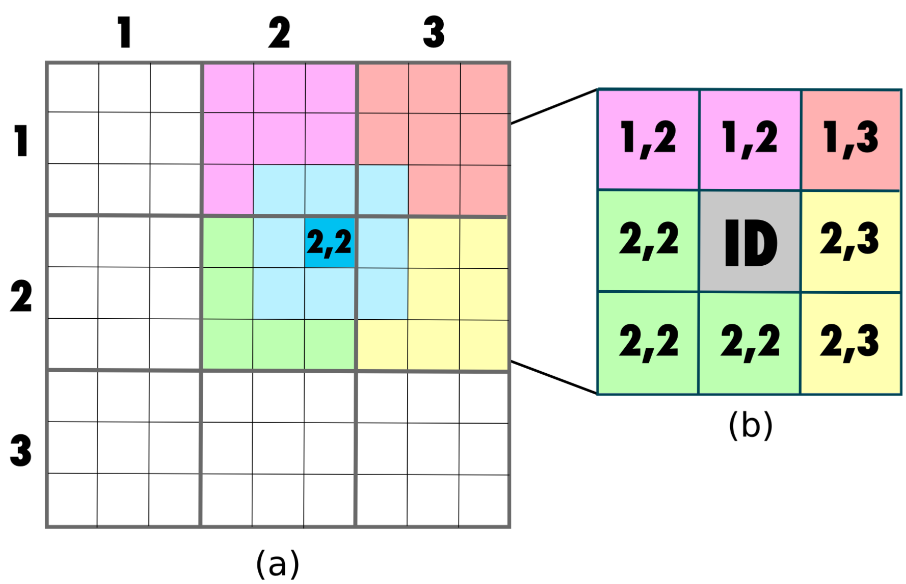


Figure 4.7: Coordinates of the participants related to the layout grid with flags and neighborhood grid.

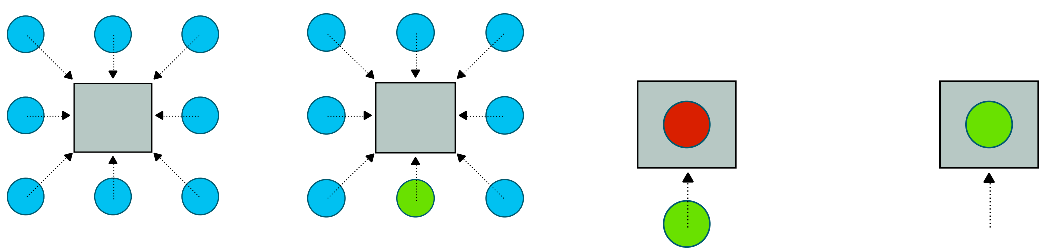
A real person occupies approximately 0.5m x 0.5m. However, our layout cells cover 1.5m x 1.5m, because we experiment with a special two-level mapping of coordinates. The model of every person has coordinates in a grid that we call *layout grid*. Cells in this regular grid have 1.5m x 1.5m and we call them *layout cells* and whole layout space is covered with this larger grid, without any holes. Every person has also 2 flags - horizontal and vertical (according to 3x3 grid, into which the cell is divided, see fig. 4.6). These flags mean position in the layout cell, depending to which part of the cell the person belongs. For the layout we need to store only width/1.5m x height/1.5m cells, where in traditional approach it is width/0.5m x height/0.5m. For the person we need to store 8 pointer values for the flags. As our crowd is sparse, therefore there are less cells we store as they are in the grid with 0.5m x 0.5m. Moreover, this reduces memory requirements.

Every participant stores it's ID from the array of crowd members. Moreover, participants also update 3x3 grid, with cell size 0.5m x 0.5m. We call this grid *neighborhood grid*, see fig. 4.7. This grid is aligned in the way that participant coordinates and flags are always in the middle. So in the middle of the neighborhood grid is participant ID (position of this cell is not important as it is always aligned with the participant). Other cells of the neighborhood grid contain coordinates in the layout grid of a cells they lay on. This mapping allows us to have easy access to the neighborhood cells, as this access is needed for collision detection and behavior control. Difference between our mapping and standard layout mapping is that our cells are bigger, therefore less memory is consumed because we have sparse crowd. Difference between our mapping and adaptive grid is that surrounding (neighborhood grid) of the participant is handled from the perspective of the participant, which brings easier access to this property. Access to the neighborhood cells is better in our approach, because we use simplicity of access in grid approaches and we store specific pointers to the cells that are aligned to participant's position. This way we have adaptive access to the cells of a layout grid that are really in the surrounding of the participant.

4.3.2 Collision Avoidance

Collision avoidance we solve in our approach in three steps. In the first step new desired coordinates with flags are calculated. We call these desired coordinates with flags *desired positions*. Desired positions are only those combinations of desired coordinates with flags, that are desired destination for some crowd members. It could happen that two or more persons have same desired position, we call these *colliding positions* and *colliding people*. In the second step colliding participants (with same desired positions) are resolved. In the third step participants actually move.

The second step is also divided into the parts. Firstly, we need to find only one person, that will move to the position. Secondly, we need to check if desired position is available (if it is not occupied). We opted for this order, because the occupied position could be available during the decision process, as we cannot move them all at time. If a position is occupied, we set person, who want to move there to a waiting status. This status will expire in another round. This way we could achieve following behavior. Therefore, crowd members could move locally on line segments, which is natural.

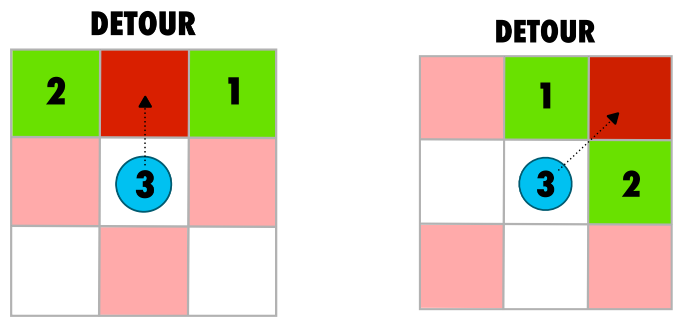


(a) (b) (c) (d)

Figure 4.8: Decision process used for finding the next person for an actual cell.

Our decision process, see fig. 4.9:

- Desired positions that are not colliding could be directly set as new positions for the participants, no decision process is needed.
- Colliding people are resolved separately, each colliding position at time. From



(a) (b)

Figure 4.9: Number 1, 2 are detour possibilities, which one is the first, depends on the behavior control, it is not hard coded. Number 3 is a previous location and a possible new location

colliding people in this position is chosen one, based on priority. Person with waiting status has highest priority.

- Other colliding people, that are not set to waiting in this step, or did not find new position yet are set to detour behavior. Currently, detour behavior is simple detour to the right, or left from the desired position. Because we have rectangular grid, detour to the left and right have two different possibilities, see fig. 4.9. Which of this two is selected depends on the behavior control, see sec. 4.3.3.

- If none of the above movements is possible (all desired positions are full, no movement in the desired direction is possible) participant will stay at old position, or change goal, depending on the behavior.

4.3.3 Behavior

Standard behavioral patterns using when simulating crowd of pedestrians is line forming and side stepping. This behavior is proper when discussing walking in the narrow pathways. On the contrary, in our environment we have large open space without narrow pathways, therefore line forming is not that important. Our behavior is goal-oriented, our agents have goals - prioritized list, each agent has one, what they want to see from an array of exhibits, we call this List of Goals *LoG*. There are different priority values for the goals, also different types of visitors could come to the exhibition. Depending on which kind it is, this LoG could be generated. Moreover side stepping is implemented as collision avoidance behavior, see sec. 4.3.2.

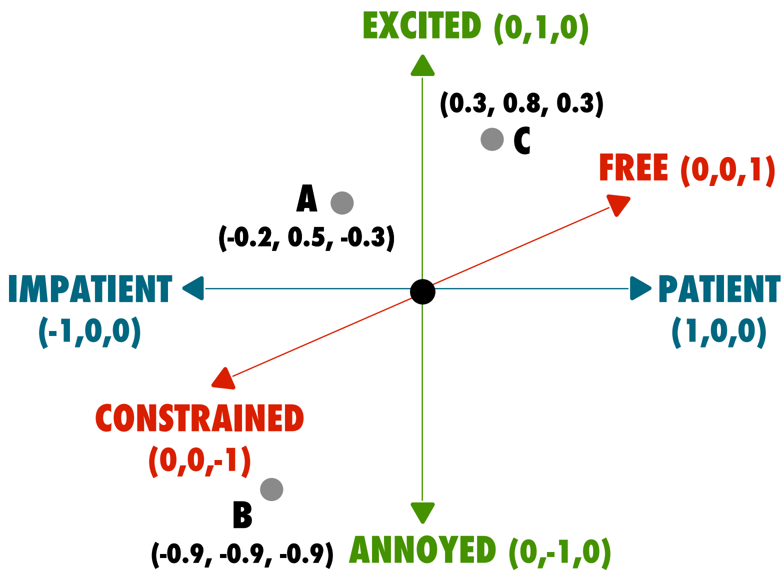


Figure 4.10: Three dimensional behavioral model.

For more complex behavior, we use three dimensional model from behavioral studies in psychology, see section 3.4.2. This model is defined in three dimensional space with three axes. Each point on these axes represents a possible mood and actual behavior is 3-vector from this space, we call it *behavioral vector*. The moods assignment depends on the situation. For our special situation we propose these three axes: impatient - patient (x-axis), excited - annoyed (y-axis), free - constrained (z-axis) as is in fig. 4.10. We propose this emotional assignment, because these are mainly changing emotions in exhibition hall. They influence timing, speed, and spacing. Usually there are exhibits and people are interested or not about them (y-axis). There are other people, that could cause overcrowded places (z-axis). These other people could cause, that given agent needs to wait to see exhibit closer (x-axis).

Every agent, when is created, has randomly set three pairs of values (each pair for limiting value decrease and increase on the axis), we call them *personality*. These values mean how fast is behavior changing on these axes. Every agent also has six three *critical values* (impatient, constrained, annoyed). When one of these three values is violated, agent goal immediately changes to an exit.

Depending on current behavioral vector, goals of the agents could change. Mainly we focus on these behaviors:

- when goal is reached, agent keeps examining the exhibit, until his/her value on y-axis keeps positive, each step this value is decreased, depending on the personality value for the axis then goal is changed to next from the LoG
- when goal is not reached, but agent waits because of overcrowded space around the exhibit, value on the x-axis is decreased, when zero is reached, goal is changed to the next
- when there are lot of people around, value on the z-axis decreases, when zero is reached agent tends to move in less crowded space
- when any of the coordinates reaches critical value, agent's goal is changed to the nearest exit

When moving to another goal, coordinates are changing each step, depending on the number of agents around, how long they are walking, how much they are excited about the goal exhibit. There are also other behaviors possible, we leave these for the future work, see sec. 4.3.4.

4.3.4 Future Work and Results

The illustrations of current result of the work is shown in fig. 4.11 where behavior of crowd in an exhibition hall is shown. This crowd admires to displayed statues and moves according to the behavior rules described above. In the future, we would like to verify our solution with psychological theories, and real life scenarios. We also need to prove hypothesis with better performance with our grid approach. Also we need to more analyze grid used here, because rectangular grid brings known problems

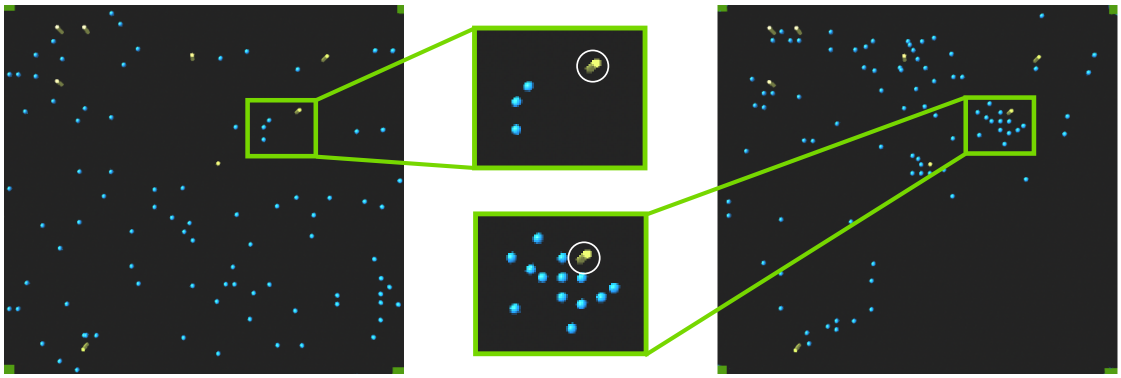


Figure 4.11: Various stages of the simulation: (left) initial step, (right) step during movement. Blue spheres represent participants that are interested in objects (yellow cylinders) and are grouped around these interesting objects.

as speed is faster when moving diagonally and also movement looks unnaturally. We would like to use hexagonal grid, this should bring more realistic movement.

Moreover we would like to incorporate better perception model with agent virtual vision, that will constrain view depending on Field of View and also will broaden the view in some directions, depending on the real Human Visual System. This will help us with collision detection, which will be more realistic. Also goal changing behavior could be based not only on behavioral model proposed here (see sec.4.3.3), but also on Visual System, where some goals could be skipped in the LoG to the beginning, when they are in the Field of View.

It would be also interesting to allow pairs or smaller groups to move together, forming hierarchical model.

5

Future Work and Conclusion

We have presented in this work problems in the topic of crowd simulation, specially in behavior control using cellular automata. We already proposed solutions, different CA for different problems in crowd simulation. Our methods partially solve different problems with novel use of CA. We tried to solve problems with CA where they were never used, therefore our solutions are not optimal and there is space for improvements, as they were mentioned in previous chapter . There are options for the motion control using CA with use of combination with motion graphs and also to find other situations, not only Flash Mob.

On the other hand the problem of populating Exhibition hall is very similar with museum environment in behavioral control, therefore psychological studies concerning this environment could be better studied [RSS+28]. Museum or exhibition hall are environments where collision avoidance behavior could be also similar to those used for walking pedestrians and we could benefit from their solutions. In the future work, we would like to incorporate improvements such as fine grid and others, enhance them to fill our specific scene, that could improve also our problem.

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