Rover Vos

Candekeep Comic books
Subtitle

MASTER THESIS

submitted in fulfilment of the requirements for the degree of

Diplom-Ingenieurin

Programme: Master's Game Studies and Engineering

Branch of study: Retelling games with Artificial Intelligence

Alpen-Adria-Universität Klagenfurt

Evaluator
Assoc. Prof. Dipl.-Ing. Dr. Mathias Luxh
Alpen-Adria-Universität Klagenfurt
Department of Information Technology

Klagenfurt, May 12, 2025

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Abstract

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Zusammenfassung

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List of Acronyms

Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Motivation and Objectives

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1.2 Structure

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Chapter 2

Topic

2.1 Classification

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Slime Molds	
Systematics	
Classification:	Living organisms
Domain:	Eukaryotes (Eucaryota)
no rank:	Amoebozoa
Class:	Slime Molds
Scientific name	
Eumycetozoa (Zopf, 1884)	
Subclasses	
Dwarf slime molds (Protostelea) True slime molds (Myxogastrea) Cellular slime molds (Dictyostelea, Acrasia) Parasitic slime molds (Plasmodiophorina) Reticulate slime molds (Labyrinthulina)	

Table 2.1: Slime molds Systematics

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- Slime molds and animals:
  Slime molds, just like animals, can move independently. However, unlike animals, slime molds do not have limbs or a subdivision of the body.
- Slime molds and fungi:
  Slime molds, just like fungi, spread via spores. However, compared to fungi, slime molds have no mycelium (filamentous cells) and no chitin (used to form structure).
- Slime molds and bacteria/single-celled organisms:
  Slime molds usually have more than one nucleus, as is the case with bacteria and single-celled organisms.

Characteristics

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[1] I am a footnote

Figure 2.1: Plasmodium of Physarum polycephalum (R. Hoyer/Wikipedia. Creative Commons)

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Distribution

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2.2 Life Cycle

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Chapter 3

Related Work

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3.1 Maze Solving

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3.2 Behavioural Intelligence and Performance

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3.3 Transport Networks

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3.4 Routing Protocols

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$$\nabla^2\psi = \delta(x - x_i), \tag{3.1}$$

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3.5 Agent-based Modeling Approaches for Mobility Systems

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3.6 Slime Mold in Education

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3.7 Self-Organizing Networked Systems for Technical Applications

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Chapter 4

Background and Methods

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4.1 Programs and Frameworks

4.1.1 Program 1

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4.1.2 Program 2

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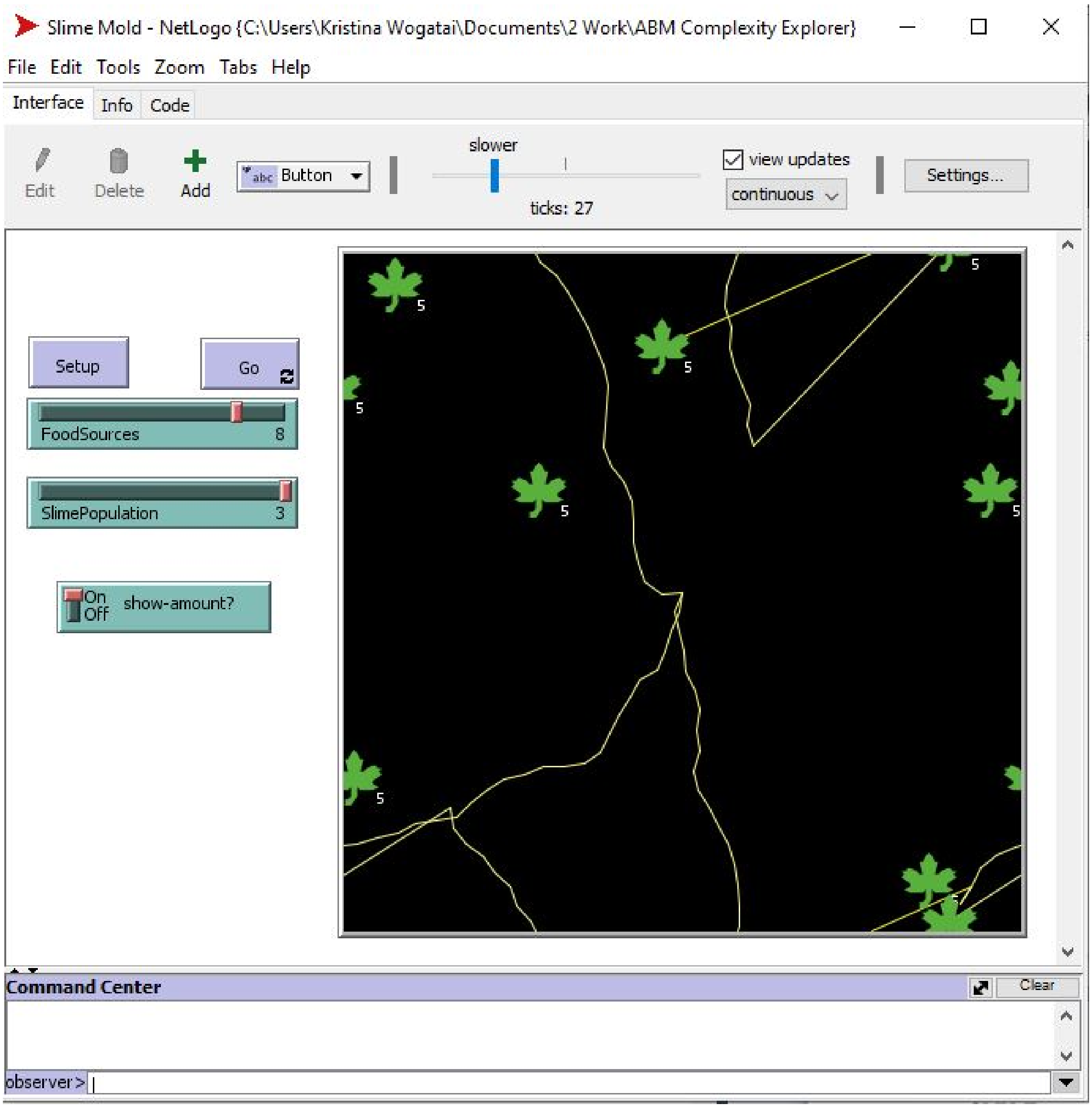

Figure 4.1: NetLogo sample program

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4.2 Models and Algorithms

4.2.1 Model A

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$$\overrightarrow{X(t+1)} = \begin{cases} \overrightarrow{X_b(t)} + \overrightarrow{vb} \cdot \left(\overrightarrow{W} \cdot \overrightarrow{X_A(t)} - \overrightarrow{X_B(t)}\right), r < p \\ \overrightarrow{vc} \cdot \overrightarrow{X(t)}, r \geq p \end{cases} \tag{4.1}$$

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$$p = \tanh |S(i) - DF| \tag{4.2}$$

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$$\overrightarrow{vb} = [-a, a] \tag{4.3}$$

$$a = arctanh(-\left(\frac{t}{maxt}\right) + 1) \tag{4.4}$$

Formula of $\overrightarrow{W}$:

$$\overrightarrow{W(SmellIndex(i))} = \begin{cases} 1 + r \cdot log\left(\frac{bF-S(i)}{bF-wF} + 1\right), condition \\ 1 - r \cdot log\left(\frac{bF-S(i)}{bF-wF} + 1\right), others \end{cases} \tag{4.5}$$

$$SmellIndex = sort(S) \tag{4.6}$$

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4.2.2 Sample Algorithm

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$$f(s) = g(s) + h(s) \tag{4.7}$$

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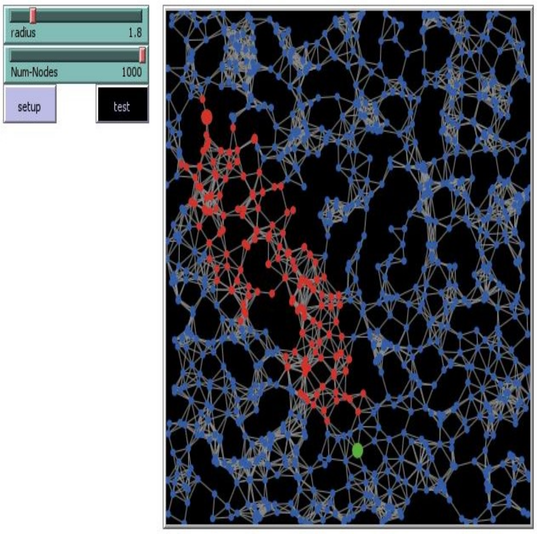

Figure 4.2: NetLogo - A* Simulation - Search

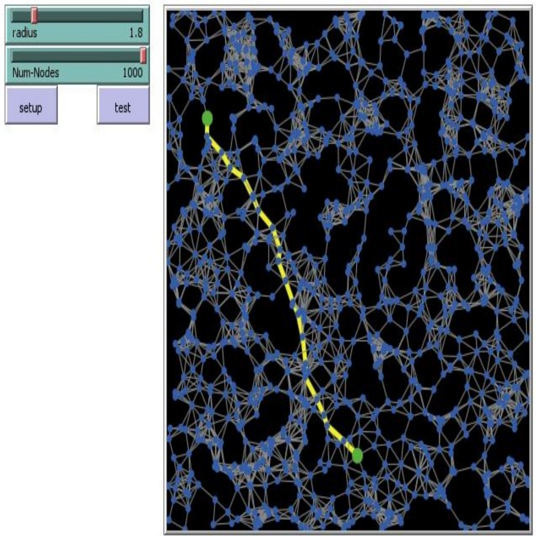

Figure 4.3: NetLogo - A* Simulation - Shortest Path

Chapter 5

Implementation

5.1 My Topic

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5.2 My Work

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5.3 My Implementation

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5.3.1 Initialization

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5.3.2 Setup

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5.3.3 Simulation Process

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Chapter 6

Experiments

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6.1 Experiments and Simulations

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6.1.1 Materials and Methods

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6.1.2 Experiment 1: Title

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Experimental Setup

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6.1.3 Experiment 2: Title

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Experimental Setup

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6.2 Results and Discussion

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Chapter 7

Conclusion

7.1 Summary

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7.2 Further Work

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7.2.1 Idea 1

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7.2.2 Idea 2

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Bibliography

Appendix A

NetLogo Code

A.1 NetLogo Main

A.2 SISMO NetLogo Main Function

```
__includes["math_functions.nls" "setup.nls"
   "network-creation.nls" "a-star.nls"]
;; 6 breeds needed in total, 3 for slime mold (plasmodia,
   pseudopodia, tubes), 1 for food source and 2 for A* algorithm
   ( networkpoints, searchers)
breed [ plasmodia plasmodium ]
breed [ pseudopodia pseudopodium ]
;; The tubes are used to indicate the shortest path between the
   center and the feed source
breed [ tubes tube ]
;; foods represent the foodsources
breed [ foods food ]
;; the networkpoints and searchers are used for the a*algorithm
breed [ networkpoints networkpoint ]
breed [ searchers searcher ]

globals [
  ;; to control the form of the visible chemical field
  scale-factor
  ;; sets the probability for pseudopodia to hatch a new
     pseudopodium
  hatch-probability
]

pseudopodia-own[
  ;; stores the path in a list of lists with x y coordinates
  path-list
```

```
]

foods-own [
  ;; each food source should have an amount of nutrients
  nutrient-value
  ;; the chemical level describes the radius of the food source
     in which the pseudopodia can perceive the food
  chemical-level
  ;; for the visibility of the chemical field
  intensity
]

tubes-own [
  ;; stores the path in a list of lists with x y coordinates
  path-list
]

searchers-own [
  memory                   ; Stores the path from the start node to
     here
  cost                     ; Stores the real cost from the start
  total-expected-cost      ; Stores the total exepcted cost from
     Start to the Goal that is being computed
  localization             ; The searchers position
  active?                  ; is the searcher active? That is, we
     have reached the node, but we must consider it because its
     neighbors have not been explored
]

patches-own
[
  light-level ;; represents the light energy from all light
     sources
]

;; setup, defines where to place which component of the
   simulation at the beginning and initialize the global
   variables
to setup
  ;; clear-all calls the clearing functions like clear-globals
     etc.
  clear-all
  ;; set global variables
  set hatch-probability 0.15
  set scale-factor 10
  ;; call make functions to create breeds
```

```
  make-plasmodia
  make-foods amount-foodsources
  make-pseudopodia amount-pseudopodia
  ;; next line is responsible for the visibility of the chemical
     concentration in the air
  ask patches [ generate-field ]
  ;; Resets the tick counter to zero, sets up all plots, then
     updates all plots
  reset-ticks
end

to go
  ifelse any? foods with [ nutrient-value > 0 ]
  [
    ask foods[
      ;; There is a bug where food sources are created randomly
         and untraceable. This causes the pseudopodia to hang on
         this food source. Because it takes negative values and
         iterates forever. With this code this bug is fixed.
      if nutrient-value < 0 [ die ]
    ]
    ask pseudopodia
    [
      let foodsource one-of foods-here
      ifelse foodsource != nobody
      [
        let path-list-to-provide-to-tube path-list
        ask foodsource
        [
          if show-nutrient-value [set label nutrient-value]
          set nutrient-value nutrient-value - 1
          if nutrient-value = 0 [
            ;; create the network for the a star algorithm
            create-pseudopodia-network turtle-set turtles-on
               patch-ahead 0
            ;; get one pseudopodia on the foodsource to set the
               destination x,y coordinate for the a* algorithm
            let one-pseudopodia-here one-of pseudopodia-here
            run-a-star 0 0 ([xcor] of one-pseudopodia-here)
               ([ycor] of one-pseudopodia-here)
            die
          ]
        ]
        ;; calculates a random float number between 0 an 1
        if random-float 1 <= hatch-probability
        [
```

```
          ;; create new child from pseudopodia, replace the zeros in the path-list to indicate, that it is a copy
          hatch-pseudopodia 1
          [
            let new-path-list replace-zeros path-list
            set path-list new-path-list
          ]
        ]
      ]
      [
        ;; movment of the pseudopodia -> bounce of the wall, movement and sense chemotaxis from food
        bounce
        wiggle
        look-for-food
      ]
    ]
    ;; if the a * buildet a tube display it
    ask tubes[
      let i 0
      while [i < length path-list - 1]
      [
        let x-1 [xcor] of item i path-list
        let y-1 [ycor] of item i path-list
        setxy x-1 y-1
        let col [pcolor] of one-of neighbors
        set i i + 1
      ]
      die
    ]
    tick
  ]
  [
    stop
  ]
end

to look-for-food
  ;; find chemotaxis in the area of a food source
  let foodsource one-of foods in-radius 5
  if (foodsource != nobody)
  [
    ;; if there is chemotaxis ahead move towards the center
    face foodsource
  ]
```

```
end

to wiggle
  rt random 40
  lt random 40
  if not can-move? 1 [ rt 180 ]
  fd 1
  ;; create a new entry for the path list (with x and y
     coordinates and 0 because the step from this pseudopodia is
     new)
  let xycoordinate (list xcor ycor 0)
  set path-list insert-item (length path-list) path-list
     xycoordinate
end

to bounce
  ;; bounce off left and right walls
  if abs pxcor >= max-pxcor - 1
  [
    ;; if "at the end of the world" face towards center and move
       one forward
    face patch 0 0
    ;; move one forward otherwise it will get stuck at the edge
       of the world
    fd 1
  ]
  ;; bounce off top and bottom walls
  if abs pycor >= max-pycor - 1
  [
    ;; if "at the end of the world" face towards center and move
       one forward
    face patch 0 0
    ;; move one forward otherwise it will get stuck at the edge
       of the world
    fd 1
  ]
end
```

A.3 SISMO NetLogo Setup

```
;;;;;;;;;;;;;;;;;;;;;;;;
;; Setup Procedures ;;
;;;;;;;;;;;;;;;;;;;;;;;;

```

```
;; create slime population
to make-plasmodia
  create-plasmodia 1
  [
    set size 5
    set shape "cloud"
    set color yellow
  ]
end

;; create pseudopodia
to make-pseudopodia [number]
  create-pseudopodia number
  [
    ;; for the pseudopias we need the same starting position as for the plasmodium. Because it spreads from the center
    set color yellow
    set shape "dot"
    set path-list []
    set path-list insert-item 0 path-list (list xcor ycor 0)
    pen-down
  ]
end

;; create food sources
to make-foods [ number ]
  create-foods number [
    set shape "circle 2"
    set color orange
    set size 2
    ;; create random coordinate https://ccl.northwestern.edu/netlogo/bind/primitive/random-float.html#:
    ;; If you want to generate a random number between a custom range, you can use the following format: minnumber + (random-float (maxnumber - minnumber))
    let randomxcoord (min-pxcor + 3) + (random-float ((max-pxcor - 3) - (min-pxcor + 3)))
    let randomycoord (min-pycor + 3) + (random-float ((max-pycor - 3) - (min-pycor + 3)))
    setxy randomxcoord randomycoord
    set nutrient-value 50 + (random (150 - 50))
    set chemical-level 23
    set intensity 50
    set label-color red
  ]
end
```

```
;; patch procedure
to generate-field
  set light-level 0
  ;; every patch needs to check in with every light
  ask foods
    [ set-field myself ]
  set pcolor scale-color orange (sqrt light-level) 0.1 ( sqrt ( 20 * max [intensity] of foods ) )
end

;; do the calculations for the light on one patch due to one light
;; which is proportional to the distance from the light squared.
to set-field [p]  ;; turtle procedure; input p is a patch
  let rsquared (distance p) ^ 2
  let amount chemical-level * scale-factor
  ifelse rsquared = 0
    [ set amount amount * 1000 ]
    [ set amount amount / rsquared ]
  ask p [ set light-level light-level + amount ]
end
```

A.4 SISMO NetLogo Network Creation

```
to create-pseudopodia-network [breeds]
  ;; extract the pseudopodia breed from the agentset to access the list of pseudopodias
  let pseudos [pseudopodia] of breeds
  ;; iterate through all pseudopodias to check if they have an intersection
  let coordinates-list [path-list] of item 0 pseudos
  if length coordinates-list = 1
  [
    ;; in case there is only one pseudopodium
    set coordinates-list lput item 0 coordinates-list coordinates-list
  ]
  let i 0
  while [ i < length coordinates-list - 1]
  [
    ;; get current coordinates from all coordinates
    let coordinates item i coordinates-list
    let j length coordinates - 1
```

```
;; we itarte backwards, to insert the intersection on the
   right place, otherwise it would mess up the order of the
   sequence
while [ j > 0]
[
  if item 2 item (j - 1) coordinates != 1 and item 2 item
     (j) coordinates != 1
  [
    let x-1 item 0 item (j - 1) coordinates
    let x-2 item 0 item (j) coordinates
    let y-1 item 1 item (j - 1) coordinates
    let y-2 item 1 item (j) coordinates
    ;; Compare current pseudopodia with itself (to also
       calculate the interfaces of itself) and compare
       current with other pseudopodias.
    ;; One doesn't need to compare pseudopodia one with
       pseudopodia two and than again pseudopodia two with
       pseudopodia one.
    ;; Therefore iterate only for example pseudopodia two
       with three, four five and so on
    let k i
    while [ k < length coordinates-list - 1 ]
    [
      ;; get coordinates to compare from the list of all
         coordinates
      let coordinates-to-compare item k coordinates-list
      let l length coordinates-to-compare - 1
      while [ l > 0]
      [
        ;; if the coordinates are a copy of a parent skip
           the comparison
        if item 2 item (l - 1) coordinates-to-compare != 1
           and item 2 item (l - 0) coordinates-to-compare !=
           1
        [
          ;; Defining the comparison coordinates
          let x-1-compare item 0 item (l - 1)
             coordinates-to-compare
          let x-2-compare item 0 item (l)
             coordinates-to-compare
          let y-1-compare item 1 item (l - 1)
             coordinates-to-compare
          let y-2-compare item 1 item (l)
             coordinates-to-compare
```

```
      ;; If the intersection points are already connected, do not perform an intersection calculation.
      if (x-1 != x-1-compare) and (y-1 != y-2-compare) and (x-2 != x-2-compare) and (y-2 != y-2-compare) and (y-2 != y-1-compare) and (x-2 != x-1-compare)
      [
        ;; calculate intersection points
        let intersection-coordinate-result intersection-point x-1 x-2 x-1-compare x-2-compare y-1 y-2 y-1-compare y-2-compare
        ifelse (intersection-coordinate-result != []) and (intersection-coordinate-result != (list 0 0 1)) and (not empty? intersection-coordinate-result)
        [
          ;; if show-intersection-points is set, than mark the intersection points with an X
          if show-intersection-points
            [
              hatch 1
              [
                set shape "x"
                set color red
                set size 1
                set xcor item 0 intersection-coordinate-result
                set ycor item 1 intersection-coordinate-result
              ]
          ]
          ;; The intersection point is set at the correct position in the coordinates list and the network around the intersection point is built.
          ;; The network points are created only if there doesn't exist a network point on this coordinate.
          set coordinates insert-item (j) coordinates intersection-coordinate-result
          set coordinates-to-compare insert-item (l) coordinates-to-compare intersection-coordinate-result
          ;; check if there are existing network points, if not create some and link them, if they
```

```
            exist create the missing one and connect
            them
        let first-point one-of networkpoints with
            [xcor = x-1 and ycor = y-1]
        let intersec-point one-of networkpoints with
            [xcor = item 0
            intersection-coordinate-result and ycor =
            item 1 intersection-coordinate-result]
        if(first-point = nobody)
        [
          hatch-networkpoints 1
          [
            setxy x-1 y-1
            set hidden? not show-network
            set shape "circle"
            set size .5
            set color blue
            set label ""
            set first-point self
          ]
        ]
        if(intersec-point = nobody)
        [
          hatch-networkpoints 1
          [
            setxy item 0
                intersection-coordinate-result item 1
                intersection-coordinate-result
            set hidden? not show-network
            set shape "circle"
            set size .5
            set color blue
            set label ""
            set intersec-point self
          ]
        ]
        ask first-point [create-link-with
            intersec-point]

        let second-point one-of networkpoints with
            [xcor = x-2 and ycor = y-2]
        if(second-point = nobody)
        [
          hatch-networkpoints 1
          [
            setxy x-2 y-2
```

```
        set hidden? not show-network
        set shape "circle"
        set size .5
        set color blue
        set label ""
        set second-point self
      ]
    ]
    ask intersec-point [create-link-with second-point]

    let first-compare-point one-of networkpoints with [xcor = x-1-compare and ycor = y-1-compare]
    if(first-compare-point = nobody)
    [
      hatch-networkpoints 1
      [
        setxy x-1-compare y-1-compare
        set hidden? not show-network
        set shape "circle"
        set size .5
        set color blue
        set label ""
        set first-compare-point self
      ]
    ]
    ask first-compare-point [create-link-with intersec-point]

    let second-compare-point one-of networkpoints with [xcor = x-2-compare and ycor = y-2-compare]
    if(second-compare-point = nobody)
    [
      hatch-networkpoints 1
      [
        setxy x-2-compare y-2-compare
        set hidden? not show-network
        set shape "circle"
        set size .5
        set color blue
        set label ""
        set second-compare-point self
      ]
    ]
```

```
                        ask intersec-point [create-link-with second-compare-point]
                      ]
                      [
                        ;; if there are no intersection points just build the network without them for the provided coordinates
                        build-network x-1 y-1 x-2 y-2
                      ]
                      ;; Links are created between the network points and these are then colored yellow to match the rest of the simulation.
                      ask links [set color yellow]
                    ]
                  ]
                  set l l - 1
                ]
                set k k + 1
              ]
            ]
            set j j - 1
          ]
          set i i + 1
        ]
end

to build-network [x-1 y-1 x-2 y-2]
  ;; check if there are existing network points, if not create some and link them, if they exist create the missing one and connect them
  let first-point one-of networkpoints with [xcor = x-1 and ycor = y-1]
  let second-point one-of networkpoints with [xcor = x-2 and ycor = y-2]
  if(first-point = nobody)
  [
    hatch-networkpoints 1
    [
      setxy x-1 y-1
      set hidden? not show-network
      set shape "circle"
      set size .5
      set color blue
      set label ""
      set first-point self
    ]
```

```
  ]
  if(second-point = nobody)
  [
    hatch-networkpoints 1
    [
      setxy x-2 y-2
      set hidden? not show-network
      set shape "circle"
      set size .5
      set color blue
      set label ""
      set second-point self
    ]
  ]
  ask first-point [create-link-with second-point]
end
```

A.5 SISMO NetLogo Math Functions

```
;; calculation of the intersection points (line-line intersection)
to-report intersection-point [x1 x2 x3 x4 y1 y2 y3 y4]
  let point []
  let t-numerator (x1 - x3) * (y3 - y4) - (y1 - y3) * ( x3 - x4)
  let t-denominator (x1 - x2) * (y3 - y4) - (y1 - y2) * (x3 - x4)
  let u-numerator (x1 - x3) * (y1 - y2) - (y1 - y3) * ( x1 - x2)
  let u-denominator (x1 - x2) * (y3 - y4) - (y1 - y2) * (x3 - x4)
  if (t-denominator = 0) or (u-denominator = 0) [
    report point
  ]
  let t t-numerator / t-denominator
  let u u-numerator / u-denominator
  ;; there is an intersection if 0.0 <= t <= 1.0 and if 0.0 <= u <= 1.0
  if (t >= 0) and (t <= 1) and (u >= 0) and (u <= 1)
  [
    set point (list (x1 + t * (x2 - x1)) (y1 + t * (y2 - y1)) 0)
  ]
  report point
end

;; next two functions are for replacing the zeros in the coordinate list of a pseudopodium.
to-report replace-zero [the-list]
```

```
  if item 2 the-list = 0
    [ report replace-item 2 the-list 1 ]
  report the-list
end

to-report replace-zeros [lists]
  report map [ i -> replace-zero i] lists
end
```

A.6 SISMO NetLogo A* Algorithm

```
; Auxiliary procedure to test the A* algorithm between two
   random nodes of the network
to run-a-star [x-start y-start x-end y-end]
  ask networkpoints [set color blue set size .5]
  ask links with [color = yellow][set color grey set thickness 0]
  let start one-of networkpoints with [xcor = x-start and ycor =
     y-start]
  ask start [set color green set size 1]
  let goal one-of networkpoints with [xcor = x-end and ycor =
     y-end]
  ask goal [set color green set size 1]
  ; We compute the path with A*
  let path (A* start goal)
  ; if any, we highlight it
  if path != false
  [
    highlight-path path
    let tube-path []
    foreach path [ x -> set tube-path lput x tube-path]
    ;; hatch tube to make it visible
    hatch-tubes 1
    [
      set path-list tube-path
      set color yellow
      set size 2
      setxy 0 0
      set pen-size 8
      pen-down
    ]
  ]
end

```

```
; Searcher report to compute the heuristic for this searcher: in this case, one good option
; is the euclidean distance from the location of the node and the goal we want to reach
to-report heuristic [#Goal]
  report [distance [localization] of myself] of #Goal
end

; The A* Algorithm es very similar to the previous one (patches). It is supposed that the
; network is accesible by the algorithm, so we don't need to pass it as input. Therefore,
; it will receive only the initial and final nodes.
to-report A* [#Start #Goal]
  ; Create a searcher for the Start node
  ask #Start
  [
    hatch-searchers 1
    [
      set shape "circle"
      set color red
      set localization myself
      set memory (list localization) ; the partial path will have only this node at the beginning
      set cost 0
      set total-expected-cost cost + heuristic #Goal ; Compute the expected cost
      set active? true ; It is active, because we didn't calculate its neighbors yet
    ]
  ]
  ; The main loop will run while the Goal has not been reached and we have active searchers to
  ; inspect. Tha means that a path connecting start and goal is still possible
  while [not any? searchers with [localization = #Goal] and any? searchers with [active?]]
  [
    ; From the active searchers we take one of the minimal expected cost to the goal
    ask min-one-of (searchers with [active?]) [total-expected-cost]
    [
      ; We will explore its neighbors, so we deactivated it
      set active? false
```

```
    ; Store this searcher and its localization in temporal
      variables to facilitate their use
    let this-searcher self
    let Lorig localization
    ; For every neighbor node of this location
    ask ([link-neighbors] of Lorig)
    [
      ; Take the link that connect it to the Location of the
        searcher
      let connection link-with Lorig
      ; The cost to reach the neighbor in this path is the
        previous cost plus the lenght of the link
      let c ([cost] of this-searcher) + [link-length] of
        connection
      ; Maybe in this node there are other searchers (comming
        from other nodes).
      ; If this new path is better than the other, then we put
        a new searcher and remove the old ones
      if not any? searchers-in-loc with [cost < c]
      [
        hatch-searchers 1
        [
          set shape "circle"
          set color red
          set localization myself ; the location of the new
            searcher is this neighbor node
          set memory lput localization ([memory] of
            this-searcher) ; the path is built from the
                                                              ;
                                                                origin
                                                                search
          set cost c    ; real cost to reach this node
          set total-expected-cost cost + heuristic #Goal ;
            expected cost to reach the goal with this path
          set active? true  ; it is active to be explored
          ask other searchers-in-loc [die] ; Remove other
            seacrhers in this node
        ]
      ]
    ]
  ]
]
; When the loop has finished, we have two options: no path, or
  a searcher has reached the goal
; By default the return will be false (no path)
let res false
```

```
  ; But if it is the second option
  if any? searchers with [localization = #Goal]
  [
    ; we will return the path located in the memory of the
       searcher that reached the goal
    let lucky-searcher one-of searchers with [localization =
       #Goal]
    set res [memory] of lucky-searcher
  ]
  ; Remove the searchers
  ask searchers [die]
  ; and report the result
  report res
end

; Auxiliary procedure the highlight the path when it is found.
    It makes use of reduce procedure with
; highlight report
to highlight-path [path]
  let reduced reduce highlight path
end

; Auxiliaty report to highlight the path with a reduce method.
    It recieives two nodes, as a secondary
; effect it will highlight the link between them, and will
    return the second node.
to-report highlight [x y]
  ask x
  [
    ask link-with y [set color yellow set thickness .4]
  ]
  report y
end

; Auxiliary nodes report to return the searchers located in it
    (it is like a version of turtles-here,
; but fot he network)
to-report searchers-in-loc
  report searchers with [localization = myself]
end
```