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Push Genetic Programme For a Mobile Robot Controller

Deliverable 1: Final Year Dissertation

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# Declaration of Authorship

I, Jacob Cooper, declare that this report titled, “Push Implementation of Biped Locomotion Control” and the work presented in it is my own. I confirm that this work submitted for assessment is my own and is expressed in my own words. Any uses made within it of the works of other authors in any form (e.g., ideas, equations, figures, text, tables, programs) are properly acknowledged at any point of their use. A list of the references employed is included.

Signed: Jacob Cooper Date: Friday 22nd November 2019

# Abstract

In this report, I look at how to apply Push to implementing a Genetic Programme for evolving robot controllers in the Webots simulation environment. I discuss evolutionary algorithms such as Genetic Programming and Genetic Algorithms. I go through all the properties of an EA and go over GAs and the unique properties of GPs along with its various representations. Although I touch on GAs, my focus will be on GPs. I go over the most basic kind of GP, the tree-style GP. Additionally, I explain Linear GP along with many of its relevant, unique traits and methods. I focus on Linear GP as is the best representation for the stack-based programming language Push and a is better for representing GPs than trees. I discuss Push’s many quirks and its newer iterations such as Push3, Plush and PyshGP. PyshGP is the tool i intend to use to implement a Push GP. I explore how PyshGP is used and how it differs from its parent (Push3). The area of Evolutionary robotics is also essential in this project; I give an overview of this subject along with many relevant papers later in this report. I also cover Webots, its competition and why it is an excellent simulation environment for my project. This report will cover how I intend to accomplish this task as well as risk management in the Project Management Plan. We cover the design choices and evaluation methods in the Design and Evaluation Strategy sections. Our aim and objectives are outlined below as well as requirements. Any resources used will be available in the Reference section at the end of the report.

# 1 Introduction

Push is a stack-based language that has a small base of dedicated researchers. For this reason its potential in certain areas is relatively unexplored. The main application of Push is in the field of genetic programming, however one area it has not been used in is that of evolutionary robotics. Evolutionary robotics is the field of evolving robots in various ways to complete a task (more in Section 2.3) . This may involve evolving the various morphologies of different robots or it may entail evolving controllers for a robot. Push has not been used for any such task. In this report I plan to fix this by showing how I will implement a Push genetic programme for a robot controller. Most of the time it is not feasible to use real robots to test a genetic programme as it can often be financially expensive. An alternative to real robots is realistic simulated environments. These environments provide a realistic way to test how a genetic programme performs (more on this in Section 2.4.2). I chose the Webots simulation environment as it is proven in the field of genetic programs (see section 2.4.1), it provides many useful tools (see section 2.4) and it is free. I plan to combine the research from paper by Ferreira, C. et al. (2014) [11] as an outline for a genetic program which I will implement in Push.

## 1.1 Aim

Investigate the use of Push genetic programming for creating a controller for a mobile robot. The purpose of this is to test Push’s capabilities when used in evolutionary robotics.

## 1.2 Objectives

* Explore morphology of robot to find a suitable robot body that can perform the tasks required by the controller.
* Create a suitable testing environment so that a robot may be suitably tested.
* Create a robot that interfaces properly with the Push GP in this environment so that we may test its capabilities.
* Explore the use of Push GP for evoloving intelligent controllers in the context of evolutionary robotics.

## 1.3 Stakeholders

The stakeholders in this report are Supervisor (Dr Michael Lones), Heriot-Watt University, Robotics Researchers, Game Developers, Companies which use robots, Creators of any code libraries I use, Creators of Webots, Users of Webots, Genetic Programming researchers and Push researchers.

# 2 Background

## 2.1 Evolutionary Algorithms

Evolutionary Algorithms (EA) take influence from nature and biology to try and solve problems.[2] It does this by employing strategies used in nature, such as evolution. Examples of this would be Genetic Programming and Genetic Algorithms. Most EA’s are either :

* Generational: meaning they create an entire new set of individuals each iteration [2]
* Steady-state algorithms: meaning they choose a subset of individuals to iterate over at a time [2]

Although genetic programming (GP) and Genetic Algorithms (GA) are slightly different, they do (generally) share a few fundamentals on how they are formed. Both generally: create a set of candidate solutions which can be tested, the best solutions are then used to derive further solutions (maybe generational or Steady-state). This cycle is then repeated until either a suitable solution is found, or time runs out. The methods described above have names and are a part of almost all GAs, and GPs they are [1] [2][7][17]:

1. Initialisation of the population
2. Fitness Assessment to find the fitness of each individual
3. Fitness Selection to select the fittest individual in a population
4. Crossover and mutation of the fittest individuals

Steps 2, 3 and 4 are repeated for the next iteration until a solution is found or time runs out. There are many variations on how to initialise the population, how to assess their fitness, and how to do crossover and mutation [1][2][7][17].

Some Algorithms may replace steps with another of their own or miss out on some steps completely. I will touch on Genetic Algorithms, but my focus here is on Genetic Programming. Below are attributes that exist for all EA’s. Further down (Sections 2.1.1 and 2.1.2), I will discuss the processes and properties that are unique to specific EA’s and their representations.

#### Initialisation

When starting a population, the most significant decision is how our population is represented. A few different representations exist depending on which EA is used and different initialisation processes exist for each of these representations [1][2][7][17].

#### Fitness Evaluation and Selection

The choice in fitness evaluation and selection can have substantial consequences on what solutions are put out [1][2]. The EA performs these processes as follows:

1. Fitness Evaluation: Each individual’s fitness is assessed usually based on a fitness function. This function considers multiple variables to sense how “well” a program has done at its given task.
2. Fitness Selection: Process in which individuals are picked for crossover and mutation. Usually, fitter individuals are more likely to be picked. However, we should allow less-fit individuals to be picked so that diversity is maintained .

Fitness Evaluation and Selection is universal across all EAs, meaning any EA can use the methods described next.

##### Tournament Selection

Tournament selection is one of the most popular methods for fitness selection in many GAs and even GPs.[1][2][17] There are several reasons for this, such as: it is not very sensitive to how the actual fitness function works, it is straightforward, requires no preprocessing, works well with parallel algorithms (necessary for running as many iterations as possible at once) and is very modifiable (able to change the size of the tournament as well as how selective it is).

Tournament selection works by first selecting a random group of individuals in a population. Then iteratively comparing them everyone in this group with another in a tournament fashion until there is an ultimate winner in that section of the population. This is done across the whole population by splitting it into ‘n’ groups, having ‘n’ tournaments and then using the winners of those tournaments for crossover and mutation.

##### Lexicase Selection

First introduced by Lee Spector (2012)[3], lexicase selection considers test cases separately rather than an aggregate like tournament selection. It begins with a pool of possible parents. These parents are slowly narrowed down through many different fitness cases which are applied one at a time. Many different methods of lexicase selection can be found by altering the criteria required to be put in this initial pool.

The most basic form of Lexicase Selection is called “global pool, uniform random sequence, elitist lexicase selection”. It has an initial pool that is the entire population; this is called “global pool”. The fitness cases are applied to each parent in a random order. The fitness case ordering is selected from a uniform distribution of all possible orderings; this is called “uniform random sequence”. Only the individuals with the best fitness for a given fitness case can survive onto the next fitness case; this is called “elitist”.

##### Epsilon-Lexicase Selection

Introduced in 2016 (Lee Spector et al.) [4], Epsilon-Lexicase Selection works in much the same way as Lexicase selection in that it has a pool of parents and a set of fitness cases. The difference is that the pass conditions for each test case are more effectively defined.

Epsilon-Lexicase in four steps [4]:

1. Initialise the pool as being the entire population.
2. Shuffle the fitness cases
3. Use elitism to select only individuals with the best fitness in each fitness case to proceed to the next fitness case.
4. If there is only one parent left, then this is our selected parent. If there is more than one parent left in the pool, then we repeat step 3 with the next fitness case. If there are no more fitness cases left and still more than one parent, then a parent is randomly selected from those remaining in the pool.

#### Crossover

Crossover is considered a macro genetic operation [7]. The purpose of crossover is to find two individuals and swap some parts in them. This is done because there is usually a good trait in both parents that allowed them to be selected. The hope is that we get a good trait from both parents , combine these traits and create an even fitter child [1][2][7][17].

#### Mutation

Mutation is considered a micro genetic operation [7]. Mutation is done to keep variation in the population. It is essential to keep our population diverse in order to stop our algorithm prematurely coming to a halt. It may think it has found the optimal solution. However, this solution may be a local optima and not the most optimal solution for the problem (global optima). [1][2][7][17]

### 2.1.1 Genetic Algorithms

John Holland conceived the first idea of genetic algorithms at the University of Michigan in 1973 [18]. A GA selects individuals one group at a time. Then it generates children from each of these groups until enough children have been created to fill the next generation. Typically this is performed over fixed-length real vectors. A GA can be represented using vectors of Boolean values, real values or integers.[2][18]

### 2.1.2 Genetic Programming

Genetic programming focuses on finding optimal small computer programming which exist in a sizeable space of possible computer programs. GPs work when there is a small space of possible programs, but it is not clear which ones are optimal. Representations are usually lists or trees. These lists/trees are all usually formed from a set of essential functions or CPU operations. The operations involved in initialisation and modification in GPs are mostly for maintaining syntactically-valid individuals. [1][2][7][17]

#### Linear GP

GPs can be represented as arbitrary-length lists of machine language instructions. Closure must be maintained while executing arbitrary machine code strings. It is essential to construct the list from a carefully selected set in order to maintain closure. For Example: If instructions are finite in length, then we can assign a unique integer to each instruction. There is usually uses a finite set of registers. These registers cause the machine code lists to operate more like directed acyclic graphs. Early instructs will affect instructs much later due to them sharing a register. Registers are selected from a register set and can either be Input registers or calculation registers. Input registers hold inputs for the program before execution. Calculation registers typically initialise with a constant and may be used to store the results of some calculation. Output registers can be defined from input registers or even calculation to store the output from a program. Another vital part of Linear GP is the instruction set. The instruction set is essentially the programming language used in the evolution of the programs. Linear GP is usually used to represent imperative or machine languages.[1][2][7]

##### Initialisation

Generation of lists depends on what domain they are required for. However, there are two general issues when initialising a list: the length of the list and populating it. Usually, Initialization is entirely random. An upper bound must be defined, and a lower bound must be defined. The lower bound may be equal to one instruction. Then when a new program is created its length uniformly chosen from between the previously defined bounds. It is essential not to make the initial length of programs too large or too small. Too large of a program will reduce the variability that can happen during evolution. Too small of a program can lead to programs not being diverse enough and potentially converging too early. [1][2][7]

##### Crossover

Crossover is done in Linear GP taking one or more values from either parent and swapping them. Crossover can be done via the “two-point linear crossover” method. [7]

###### Two-Point Linear Crossover

Two-point linear crossover begins by taking a parent and selecting two points between zero and the length of the parent. Then do the same to another parent. Then swap the values inside these two ranges between the parents. One problem is that a child may become too large if the sections selected are not equal. One way to counter this would be to ensure when selecting sections of the parents, that the sections are of equal length. [7]

##### Mutation

Linear GP Mutation can be done in many ways, such as: Randomly replacing an instruction with another, that takes in the same number of inputs; Randomly replacing a constant with another of the same type or Randomly replacing a register with another register

If only one genetic operator is used, then it is likely that the variation will not be high. The evolution will progress more precisely with smaller changes throughout each iteration and would be more exploitative. However, if multiple genetic operators are used at once, then it will make much more significant changes between generations and is more explorative. Usually, micro mutations and macro mutations are both used each iteration; an example of this would be Crossover and Mutation as explained above. [7]

#### Tree- Style representation

The first GP, as represented through trees and was introduced by JR Koza (1992) [19]. This style represents a tree of nodes, each representing either an instruction or terminal. Each instruction node’s children are essentially the input for the instruction. For example, a node may be a ‘+’ instruction and have two children of a ‘1’ and ‘2’; this simple tree would represent “ 1 + 2”. The nodes of tree representations may be restricted to how many children they can have; this is an essential quality for the construction of trees in initialisation. [1][2][17][19]

##### Initialisation

To produce a tree: the GP selects iteratively from a function set. In this function set, each member has a set arity. Arity is the number of children a node has. Nodes with zero arity are leaf nodes, and nodes with greater than or equal to one arity are either a branch node or the root node. In order to build a valid tree, we must follow these rules. [1][2]

One conventional algorithm for initialisation is the Grow algorithm. In the “Grow” algorithm, a tree is built from the function set in a depth-first manner up to a maximum depth. Another algorithm “Full” is very similar to “Grow” except the only difference is “Full” forces the tree to be maximum depth whereas “Grow” does not. [1][2][19]

An algorithm that strikes a balance between “Full” and “Grow” is “Ramped half-and-half”. “Ramped half-and-half” gives a 50% chance to “Full” and “Grow” and usually randomly selects depth from 2 to 6. [1][2][19]

##### Crossover

In Tree-style GP, crossover is performed by swapping subtrees between two parents.

One of the most basic ways of doing this crossover is One-Point Crossover [1][2][ 20]:

###### One-Point Crossover

“One-Point Crossover” as proposed by Poli and Langdon (1998)[20] works similarly to Standard crossover in that it picks one point and swaps the corresponding subtrees. It is typically done in two stages to account for diversity between trees.

1. Traverse both parent trees to find nodes of same arity along a path which also has the same arity (mainly looking for parts in the parents which have the same shape)
2. Select one random link with uniform probability along this path and swap the subtree after it.

One of the essential properties of the One-Point Crossover method is that it makes it easier to see which area of space is likely to be searched by the next generation. [1][2][20]

It is important to note that without mutation One-Point Crossover converges quite quickly due to there being no variation from the initial population. To keep this from happening we must mutate. [1][2][7][18][20]

##### Mutation

Mutation in Tree-style GP is performed by selecting one or more nodes to be randomly changed. The two most basic forms of mutation in Tree representation GPs are Subtree mutation and point mutation. [1][2][18]

###### Sub-Tree Mutation

Starts by picking a random mutation point in a given tree. Then swap this node and its subtree with a randomly generated subtree using an algorithm such as Full or Grow. Normally, Grow with a max depth of 5 is used for the generation of the subtree. Sub-Tree Mutation suffers from a similar problem as standard crossover as mostly leaf nodes are picked and so not much is changed. To remedy this, we do the same as before: pick branch nodes 90% of the time and leaf node 10% of the time. [1][2]

###### Point Mutation

Start by choosing a random mutation point in the Tree. Take the value of this node. If it is a branch node, replace it with a value from the function set that has the same arity. If it is a leaf node, replace it with a value from the terminal set. For example, a “+” operation could be replaced with a “\*” operation as they both have an arity of two or a “1” could be replaced with a “2” as they both have zero arity (e.g. are leaf nodes). If no function matches the arity of a selected node, then nothing happens. Subtree mutation affects one tree, whereas point mutation is on a per-node basis.[1][2][18]

### 2.1.3 Linear vs Tree Representation

Tree-based GPs requires the construction and traversal of a tree. These tree properties means it takes up more memory and lengthens the fitness evaluation time compared linear GP. Linear GP uses stacks to decode and evaluate individuals and so saves on memory and time. Linear GP also shows the same amount of capability as tree-based GP for solving problems. [31] It has been shown to solve a multitude of problems such as the classic symbolic regression problem.[31] The symbolic regression problem is the search of a space of mathematical expressions to find a best-fit solution to a dataset. [2][7][31]

## 2.2 Push

Push is designed to have a completely uniform syntax so the ease the process of generating code that manipulates code (say for auto constructive evolution). Push also supports a multitude of different data types as well as recursion and subroutines. It is an extension of other stack-based programming languages. [5][6][9].

The Push features of multiple data types, modules and complex control structures such as recursion means that this language is incredibly expressive. It is also Turing complete which means it can produces any computer program. Being turing complete and this expressive means this language is able to express any computer program with ease. [30]

A push program consists of a string of instructions, constants and parenthesis. There is only one syntax rule: balance the brackets. The instructions found in these strings take their arguments from a Global stack. Each data type has one global stack and instructions push their outputs onto these global stacks. It is written in postfix notation, meaning that for a human might be a little challenging to read it. For example a simple “1+2” operation could be defined like so: (integer 1 2 +) which is far from the simple “ 1 + 2” that we commonly know.

When implementing the evolution of multiple data types, we would typically use strongly typed genetic programming. The problem with this is there is substantial syntax restriction imposed on passed data to ensure the types match what they are supposed to be. This problem can limit options for crossover and make the evolutionary process far more complicated than It needs to be. Push breaks free of these problems with its uses of stacks. [5]

Some instruction (such as ‘+’) may be skipped if there are not enough arguments on the argument stack. So for example if a program reads ‘integer’ it will be stored in the type data stack, then if a ‘+’ method appears it first looks at the type stack to see what type ‘+’ is. The system does this because ‘+’ could have multiple types (e.g. integer/string). Is there is no type on the stack then it will resort to a default. This default has a list of types consisting of Integer, Boolean, code, type, name in that order from top to bottom. From this default, it will pick the highest type applicable. So an appropriate type will always be found for a push operation. [5]

There are a few operations implemented for all data types: pop (return the item on top of the stack), dup (duplicate item on top of stack and push it to stack) and swap (swaps the two highest items in the stack). [5]

The parenthesis in a push program are only there for structure and do not have any real effect on execution. [5]

Push also allows for code manipulation through its ‘code’ data type, which inherits from the ‘expression’ data type. [5]

A vital instruction in code manipulation expressions is the ‘quote’ instruction. When executing the ‘quote’ instruction, the next piece of code to go through execution will be pushed to the code stack rather than being executed. [5]

The “do” instruction recursively calls the expression on top of the “code” stack, mostly it is a way of executing the code on the “code” stack which was put there by the “quote” instruction. A variant of “do” is “do\*” which does the same operation except it pops the code from the “code” stack first. [5]

Code is pushed to the “code” stack before execution when first submitted to the interpreter. This can then be used the “quote” and “do” instructions to implement recursion. [5]

The “if” instruction executes the top two items on the code stack. It also checks the top element of the “Boolean” stack. Depending on what value it finds there, it may discard the rest of the code stack. [5]

Due to all the instructions which cause recursion, guards against non-termination are needed. To accomplish this, a limit is put on how many instructions can execute for every top-level call of the interpreter. [5] If this limit is exceeded, execution is terminated and the “results” left on the stacks can either be used or discarded.

The “name” data type along with the “get” and “set” instructions allow us to store items of any type as a variable; this includes code for named subroutines ( which are much like functions in languages such as Python and C). If a symbol is encountered that is not either an instruction name or a constant, then treat it as a “name” constant and push it to the “name” stack. Then this symbol can then be changed, using the “set” instruction, or read from, using the “get” instruction. [5]

### 2.2.1 PushGP

PushGP is a Push implementation of Genetic Programming. It uses basic Genetic Programming Implementations. It randomly generates a population of initial programs in its initialisation. It takes the fittest programs and select them (plus some none fit programs to maintain diversity) for breeding through the Fitness evaluation phase. Then new individuals are created with mutation and crossover from the selected individuals. The chosen fitness selection is tournament selection. Mutation picks a randomly chosen sub-expression and swaps it with another randomly chosen sub-expression. Crossover swaps one subexpression of an individual with the sub-expression of another. [5]

### 2.2.2 Push3

Push3 is the newest version of Push in which many versions derivate from (such as pyshgp[6]). The most significant change is the new “exec” stack which stores expressions, instructions and literals. The values on the stack are values that are to be executed hence then name. It is independent of the code stack which can still be used for code manipulations. The exec stack holds the code queued for execution and is continuously executed upon. [8][9] The basic process of executing a program (P) in push3 is as follows:

1. Push P onto the EXEC stack.

2. While the EXEC stack is not empty, pop and process the top element of the EXEC stack, E:

(a) If E is an instruction: execute E (accessing whatever stacks are required).

(b) If E is a literal: push E onto the appropriate stack. (c) If E is a list: push each element of E onto the EXEC stack, in reverse order.

(Lee Spector 2005) [9]

“quote” instruction now copies the top of the “exec” stack to the “code” stack. Previously, loops where done natively in languages that implement Push (such as python). Now it can be done by pushing a series of elements to the “exec” stack. When the loop is executed the elements on the “exec” stack are sequentially executed. Previously names have been bound to variables by the “get” and “set” instructions. Now, instead of using a quoted value on the “code” stack and using the “set” instruction, the “define” method on the “exec” stack is used. Executing subroutines is also more straightforward with them now being executed directly by calling just the name of the subroutine. Previously a “get” and “do” command would also accompany the name of the subroutine. [8][9]

### 2.2.3 Linear Push (Plush)

In Plush, linear genomes called Plush genomes are used to represent programs. A genome is a way to represent a program. These Plush Genomes are a linear set of instructions and literals which translate to a push program before execution. Storing the push program like this allows us to perform genetic operations uniformly across the whole genome. Plush also uses “epigenetic” markers. It does this to help translate the Plush genome into a Push hierarchical structure for fitness testing. Inserting open parenthesis to indicate the start of code blocks and epigenetic markers to determine where the code blocks close. Open parentheses are inserted when an instruction is called. Doing this allows for instructions to take code blocks from the “exec” rather than a single instruction. [21]

#### Plush Genome to Push Program

Push program tree is constructed depth-first from the genome. Each instruction from the genome and its arguments are appended to the end of the Push Program. If the instruction has no arguments, it just appends the instruction. However, if they do have arguments, then the instruction is appended, followed by several code blocks corresponding to the number of arguments. For Example, two code blocks will follow an instruction which takes two arguments from the “exec” stack. Inside these code blocks, there may be further instructions which the same process will be performed on, meaning ther may be nested code blocks. The instructions indicate the opening of code blocks and the “:close” epigenetic marker indicates the closing of code blocks. The “:close” marker indicates how many open code blocks to close by way of a proceeding number. If this number were to exceed the number of open code blocks, then all code blocks are closed. If the end of the Plush genome is reached with code blocks still open, then these blocks are automatically closed. [21]

### 2.2.4 PyshGP

PyshGP is a Python implementation of the push language. It gives a basic push instruction in Python. There are five standard data types that each have their own set of instructions. These data types are boolean, character, code, integer, float and string. There is also typecasting present in PyshGP that allows conversion of one type to another. This is done by moving the relevant element from one stack to its new type stack. [6]

An example would be the “integer\_to\_boolean” instruction that takes the top element of the integer stack and pushes a “False” to the Boolean stack if this integer is zero and “True”. Vector types also exist for some data types. These types also come with basic vector operations such as appendage, splitting and concatenation. Standard stack instructions exist for all stacks, these instruction include:

* dup: copy the top element in the stack
* swap: swaps the top two elements in the stack
* flush: remove all elements from the stack
* stack-depth: get the size of the stack and push this number to the integer stack
* yank: takes the integer from the top of the integer stack and uses this number as an index to find an element which is moved to the top of the stack
* eq: compares the top two elements in the stack and pushes a “True” to the Boolean stack if they are equal and pushes a “False” otherwise

[6]

These are only a few of the instructions present in pyshGP. The other instruction would be more akin to operations seen in languages such as Java and Python. [6]

It is possible to define new instructions if needs be. All new instructions are an instantiation of the Instruction class. This class must have a function, which takes in a PushState object and returns an altered PushState object. Every instruction uses the Instruction class, and they are stored in a set of registered instructions. Any new instruction must instantiate a new Instruction object and add it to this registered instruction set. [6]

#### PyshGP Genetic Programming

There are two ways to determine fitness. We could use a Fitness value, which is a number out of one - hundred indicating how close to optimal a solution is (with zero being the least and one-hundred being the most). Alternatively, we can use an Error Value which is a positive number indicating how far away a solution is from optimal (with zero being the most optimal). In both methods, the user has to define either a “fitness function” or an “error function” to calculate the fitness value and error value, respectively. The Pysgp system favours the “Error” approach. The error function defined must take in a push program along with a set of training cases. An error value is calculated for the program for each training case which then return as an “error vector”. An individual will hold this “error vector” value along with the value of all the error values combined called the “total error”. This storage method allows the use of either in fitness selection operations. [6]

Three fitness selection methods are supported. These are:

* Lexicase Selection (See “Fitness Evaluation and Selection” under section 2.1)
* Epsilon-Lexicase Selection (See “Fitness Evaluation and Selection” under section 2.1)
* Tournament Selection (See “Fitness Evaluation and Selection” under section 2.1)

Push programs can be represented more linearly, doing so will allow us more flexibility in using genetic operators. This can be achieved by using Plush Genomes (see section 2.2.3). These Plush genomes can also be easily converted to Push programs for error evaluation. Uniform mutation is the only form of mutation currently supported in Pyshgp. Additionally, the only recombination operator available in pyshgp is “alternation”. The user can define the parameters and tunable properties of these two genetic operators. Other values users can specify are the percentage use of each genetic operator to produce the next generation. [6]

## 2.3 Evolutionary Robotics

*Evolutionary Robotics is the area of study that involves evolving a suitable controller for a robot through some method of artificial evolution. To start, a robot must be designed to perform a task. This robot consists of multiple layers where each layer is responsible for one behaviour. Usually, to coordinate necessary behaviours, trial and error would be used. This is infeasible as problems grow in complexity. Evolutionary Robotics is a suitable solution for this problem. Instead of using trial and error, we can use an Evolutionary Algorithm (such as Genetic programming) to find a suitable program. This is done through the basic EA process of defining a fitness function (or indeed error function )then finding gradually fitter and fitter control programs based on the robot’s interaction with the environment. [10]*

### 2.3.1 Genetic programming Applied to Biped Locomotion Control

The paper by Ferreira, C. et al. in 2014 [11] is of central importance to this report (more on this in Section 4). This paper attempts to use Genetic Programming to allow bipedal robots to detect its environment and navigate it effectively. The authors use Central Pattern Genenartors (CPG) and sensory information to control a single leg. The CPG is made up of multiple rhythmic and unit motion pattern generators to simulate the movement pattern of a single leg. The two CPG of each leg communicate with each other to maintain coordination when they attempt to walk. 4 mathematicall equations generate locomotion.The authors uses four different GPs to represent the four equations. Tree-representation is used to represent each GP. Leaves of the tree took the form of either variables, constants or sensory inputs. The function set used was: SF = {sin, cos,∗,+,−, /, exp,sigmoid,step} .

Webots is used as the simulator because it can guarantee that the GP does not generate impossible joint positions.

The authors propose two controllers, one that uses sensory information and one that does not. This is to show the difference that sensory information can make on a robots ability to traverse an environment.

The initial population is created by the ramped half-and-half method (section ) with a max depth of 25 along with ten hand-crafted individuals to see how they compare to the GP generated ones. The fitness of an individual is calculated by a carefully selected fitness equation which punishes falling over and rewards individuals who travel the furthest forward with least lateral movement. Tournament Selection is used with tournament size of 10 to select individuals for breeding. Crossover and mutation are then used with a rate of 0.8 and 0.3 respectively. Other evolution parameters used are a population size of 100 and the number of generations restricted to 100.

The authors first tested their robot in a flat ground scenario where robots are tasked with moving as far forward as they can in 30 seconds. Upon testing, it was found that the final GP individuals for both controllers performed far better than the hand-picked ones. This shows that GP is capable of creating robot mobility solutions much more effectively than humans are.

The second test was in a sloped ground scenario. In which a robot is confronted with sloped ground ahead of it which it must traverse. The sloped ground forces the robot to adapt and is an effective way of testing if the GP generated locomotion can adapt to different environments. The controller without sensory information was unable to fulfil the task whereas the controller with sensory inputs was able to navigate up and down slopes. Additionally, the controller with sensory inputs had a smoother walking pattern compared to the other controller. The ability of the GP to complete the task only with sensory information proves that it is vital in creating an adaptive GP.

### 2.3.2 Applications in Genetic programming

There have been many different uses of Genetic Programming in evolutionary robotics. Such as these:

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | Robot Used | Type of  GP used | Application | Notes |
| Wolff, K. & Nordin, P., 2003.[15] | Bipedal | Linear | Controller for bipedal motion | Uses first principles as a learning technique |
| Lee, W.-P. et al.1997 [16] | Two-wheeled -  Khepra | Tree | Evolve Behavior Primitives and Arbitrators for Mobile Robots | Early paper, nothing too unusual |
| Kala, R., 2012[26] | Multiple | Coevolutionary, Linear | Multi-robot path planning | Robots have to navigate a grid-style lane layout |
| Lazarus, C. and Hu, H., 2001, [27] | Two-wheeled -  Khepra | Tree | Evolve Robot Behaviours | Uses LISP which is more akin to a linear representation |
| ] Perez, A.L.F.,2008 [28] | Two-wheeled -  Khepra, Multiple | Linear, Distributed | Using new GP variation to evolve mobile robots | Uses the evolutionary control system |
| Sharabi, S. & Sipper, M., 2006 [29] | Twin Two-wheeled sumo bots | Tree | Evolving sumo bots to fight each other | Tree style worked quite well, tests many different GP methods such as coevolution vs single population |
| Ferreira, C. et al., 2014 [11] | Biped | Tree | Using sensory information to evolve a biped locomotive | Each individual has four chromosomes for the four stages of locomotion. Each chromosome represented by tree-style GP |

It seems that papers generally dropped Tree-style representation for List –style representation as GP became more developed (more on this in section 4). However, some still used Tree-style representation as it worked well for their application(Sharabi, S. & Sipper, M., 2006 [29]).

Genetic Programming has been widely used in Evolutionary robotics as seen previously. However, one area which has had no research is a Push implementation of genetic programming for producing a mobile robot. This project aims to fix this.

## 2.4 Webots

Webots is a realistic platform for simulating mobile robots. It provides an environment to model, prototype and simulate robots in a variety of situations. It has real, commercially available robots in the simulations ready to be used for testing. [13][14]

Many parameters can be define for our robot such as shape, colour, texture, mass and friction.

Many different sensors are available for each of the robots to help it sense its environment such as distance sensors, range finders, light sensors and more. [13][14]

An environment can be built in which to simulate a robot. This environment is customisable with different obstacles, different terrain and various other items. [13][14]

Webots uses virtual time so that simulations can be run much faster (up to 300 times) than what would be possible in real life. The simulation can also be adjusted to suit a specific goal, such as accuracy or speed. Included in this simulation is a step-by-step which allows us a detailed view of how the robot behaves. [13][14]

Webots is available for a multitude of languages such as the API’s for C and Python. [13][14]

### 2.4.1 Application of Webots

Webots is a well-used platform in the world of Genetic Programming. Use of Webots is present in many projects such as the 2014 paper by Pedro Silva, Christina P.Santos, Vitor Matos and Lino Costa [12]. In this paper, Webots is an evaluator for a controller implementing genetic programming which controls a biped locomotion robot. Another application is one of the primary papers of this project. The 2014 paper by [César Ferreira](https://ieeexplore.ieee.org/author/37085378197), [Pedro Silva](https://ieeexplore.ieee.org/author/37719072600), [João André](https://ieeexplore.ieee.org/author/38667548900), [Cristina P [11]. Santos](https://ieeexplore.ieee.org/author/37067256500)and [Lino Costa](https://ieeexplore.ieee.org/author/37332955200) creates a biped locomotive controller in Webots using Genetic programming. These are only a few of the many papers which show Webots effectiveness in this area.

### 2.4.2 Other simulators and Webots

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | Realistic Physics | Easy use of EA’s in the environment | Customisable  Environment | Multitude of Sensors | Many different forms of robots | Is free |
| Webots[13][14] | Yes | Yes | Yes | Yes | Yes | Yes |
| Gazebo[22][25] | Yes | Fairly | Yes | Yes | Yes | Yes |
| Microsoft Robotics Developer Studio[23] | Yes | No | Fairly | Not a lot | Not a lot | Yes |
| Robot Virtual Worlds [24] | Yes | No | Yes | No | Handful | No |
| V-REP[22] | Yes | Fairly | Yes | Yes | Yes | Yes |

# 3 Requirements

In this section I will list and explan the various requirements of my project. Each requirement is labeled with a MoSCoW value indicating how important it is to the project i.e. “Must” is necessary for the project to be complete. A complete table of my requirements and relevant information about them is available below.

## 3.1 Explaining the requirements

Requirment 1 makes sure I have a functional robot body that I can use in Webots. Requirment 2 requires that I have a suitable flat ground environment in which to test my GPs capabilities. Requirement 3 ensures that the sensors put on the robot are suitable enough to reliably detect its surroundings so that it can provide suitable information to the fitness function. Requirment 4 is all about making sure I have made an initialization method that starts my population in my GP. Requirement 5 makes sure I have a fitness function that can reliably give an accurate fitness for each individual programme in the population. Requirement 6 requires that I have a fitness selection method that selects individuals for breeding by selecting the highest fitness individuals along with some lower fitness individuals so that the population stays diverse. Requirement 7 ensures that I have genetic operatore (e.g. Crossover and Mutation) that produce a diverse next generation that improves on the previous generation. Requirement 8 is all about making sure the robot knows when it has successfully reached its goal (or indeed ran out of time) so that it can terminate its simulation. Requirement 9 is a colmunation of requirements 4 – 7 and aims to have them all combined and working together to produce a valid and succeful GP. Requirement 10 is a test to see how well (if at all) my robot controller works on flat ground. Requirement 11 requires that a environment with a suitable (not too steep, not too gradual and suitably placed) slope is placed in the Webots environment so that I may test the robot on it. Requirement 13 is to make sure that the initial population is diverse enough so that we don’t have a premature conversion while still being valid. Requirement 14 is similar to Requirement 13 in that it ensures that the next generation produced is diverse and valid. Requirement 15 is a more advanced requirement that specifies the creation of an object for the robot to navigate around in Webots. Requirement 16 is the testing of our robots ability to navigate around the block in it’s path. Requirement 17 is the putting various obstacles in the Webots environment for the robot to navigate. Requirement 18 tests whether the robot can navigate around the various obstacles.

|  |  |  |
| --- | --- | --- |
| Requirement | Functional/Non-Functional | MoSCoW |
| 1.Robot Built in Webots | Functional | Must |
| 2. Flat environment built in Webots with start and endpoint | Functional | Must |
| 3. Robot has enough sensors to supply fitness function | Functional | Must |
| 4. Initialisation method successfully implemented in Pyshgp | Functional | Must |
| 5. Fitness function implemented in Pyshgp | Functional | Must |
| 6. Fitness selection method implemented in Pyshgp | Functional | Must |
| 7. Genetic operators successfully implemented in Pyshgp | Functional | Must |
| 8. Robot can detect when it has reached the endpoint | Functional | Must |
| 9. Have a complete Genetic program implementation in Pyshgp | Functional | Must |
| 10. implementation tested on flat terrain | Functional | Should |
| 11. Steep Terrain added to Webots environment | Functional | Should |
| 12. Implementation tested on Steep terrain | Functional | Should |
| 13. Initialisation method ensures a diverse population and valid | Non-Functional | Should |
| 14. Genetic operators ensure we maintain diversity and validity in the population | Non-Functional | Should |
| 15. Simple block in the way of path implemented in Webots | Functional | Could |
| 16. Implementation tested on finding path around block | Functional | Could |
| 17. Various obstacles implemented in Webots Environment | Functional | Would |
| 18. Implementation tested for all obstacles | Functional | Would |

# 4 Design

We will take the design for the robot, its fitness functions, its initialisation, its genetic operators and testing parameters from the 2014 paper on Genetic programming applied to biped locomotion. We will implement this in the Push programming language, more specifically the Python implementation of it (pyshgp). As in the paper, the environment I use will be Webots. However, if this proves to be too complicated to implement, then we will decide to create a new fitness function, initialisation method, genetic operators and testing parameters. The difference is that it will be much more straightforward and possibly less effective but more realistic to implement. We chose the Webots simulator as it performs the same as most other platforms. Webots also provides us with multiple already available robots and many successful implementations of GPs within it. Some platforms are inferior to Webots in terms of Customizability and integration of GP testing (Microsoft Robotics Developer Studio). Other Platforms, such as Gazebo are quite similar to Webots. Gazebo would serve as a good backup, but they lack the amount of proven success in GP that Webots has (See section 2.4.2). I chose to use Push for a few reasons: It is a expressive turing complete language meaning it can express many programs with ease, it is linear so is perfect for implementing lineargp (as tree-based GP can be quite restrictive) and it hasn’t been used in evolutionary robotics, an area which I think it may be very useful. (add in why linear over tree)

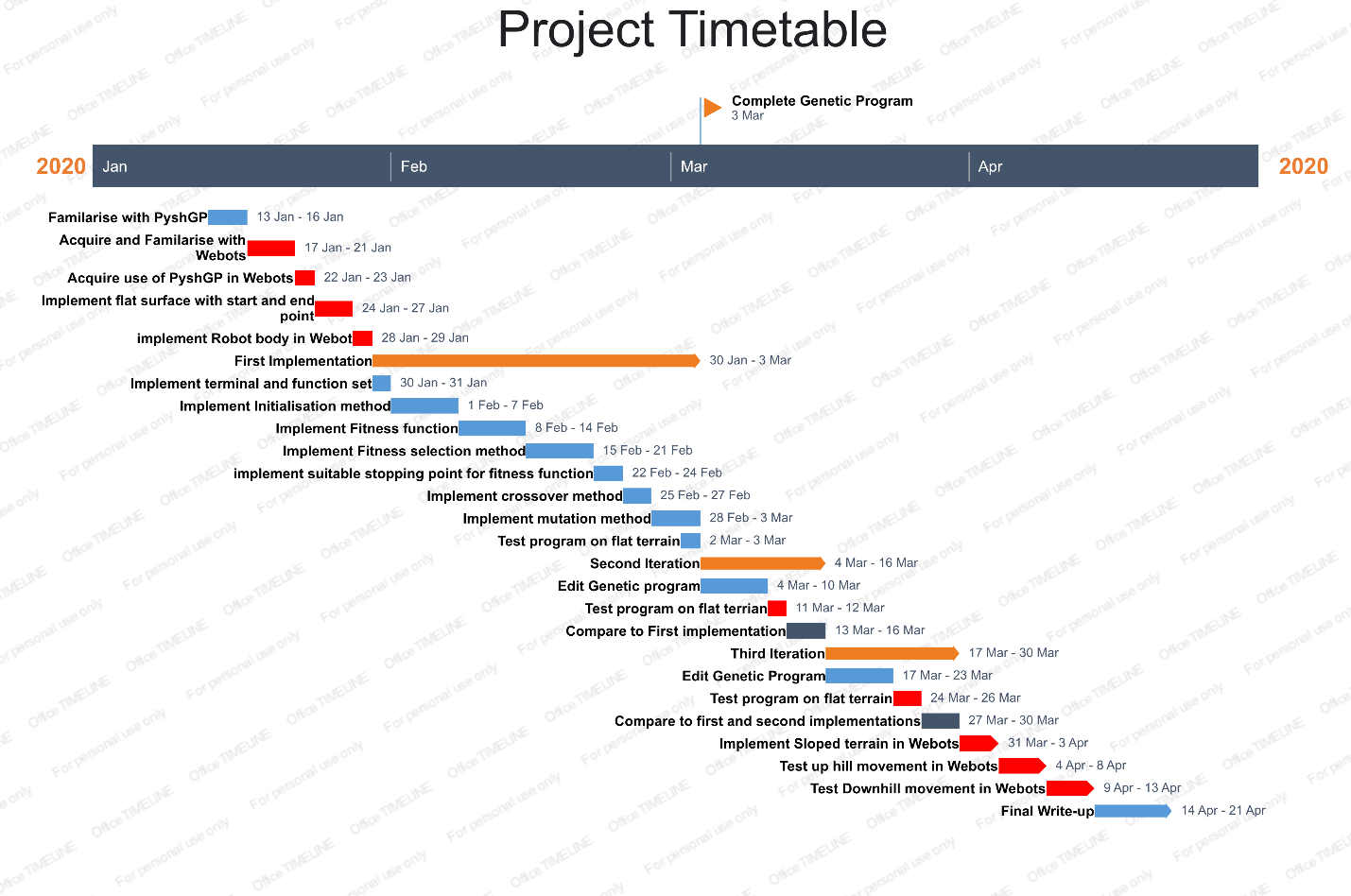
# 5 Evaluation Strategy

The two primary training environments outlined in Genetic Programming Applied to Biped Locomotion Control with Sensory Information (Ferreira, C. et al., 2014 [11]) are Flat ground and Sloped ground. When training is complete, we will test the robot on similar flat terrain but change the orientation and distance to the goal in evaluation. For the sloped situation, we will change the angle of the slope and test the robot’s climbing and descending of this slope. We make these changes to show that our GP is not constrained to evolving for one situation but can evolve for any situation with flat or sloped ground. We will show how the morphology of the robot has effected its training and constraints put on it. We will show how effective Push has been in implementing the robot by:

1. tracking its time to convergence,
2. Noting any anomalies that pop up during programming or training
3. The methods used to get our program to work.

# 6 Project Management Plan

## 6.1 Timetable



## 6.2 Risk Analysis

|  |  |  |
| --- | --- | --- |
| Risk | Likelihood/Impact | Mitigation |
| Task takes longer than expected | High/Medium | Meet with supervisor and discuss what to prioritise |
| Implemented GP can not find a path to goal | Low/Medium | Readjust parameters and re-run tests or change some algorithms in the GP |
| GP is too complicated to implement | Medium/Medium | Write simpler GP |
| Unable to have a successful moving robot | Low/Medium | Change body used or look to fix the current body |
| Unable to interface PyshGP with Webots | Low/Medium | Change to another version of Push or choose another testing environment |
| Unable to get Webots working | Low/Low | Change environments to another such as Gazebo |
|  |  |  |

# 6.3 PLES (Proffesional, Legal, Ethical and Social) Issues

My project is about creating and testing a robot controller. This requires no interaction with any users, as such it doesn’t face any ethical or legal issues relating to this. However, it still does have some issues to address.

### 6.3.1 Profesional Issues

The code I written will make use of Pythons class system to structure code so that it is readable and each class is designed around a specific domain. I plan on commenting code as I go so that it is clear what each aspect does. I will be using many different libraries, all of which will be referenced properly and code will adhere to the standards specified by British Computing Society codes of conduct. Any resources I use throughout the project will be referenced accordingly

### 6.3.2 Legal Issues

I will be using third party software in my development of this project , for example Webots. Any such libraries or environments I use will be properly referenced and adhere to any copyright that the maker holds for this software.

### 6.3.3 Ethical Issues

This software creates an AI, so it is important that the software is doing as we expect. I plan on testing the software at each iteration and recording its behaviours. If it is doing anything unexpected or unwanted I will change the code so that its behavior falls in line with what is predicted. The controllers will be programmed to only to sense and traverse its environment. This means it poses no threat to any such animal or human as it has no scope for interacting with them.

### 6.3.4 Social Issues

There are no social issues as this project doesn’t involve anyone other than myself and my supervisor.

# 7 References

[1] Poli, R., Langdon, W., McPhee, N. & Koza, J., 2008. *A field guide to genetic programming*. [S.l.]: Lulu Press.

[2] Luke, S. (2015). Essentials of Metaheuristics.

[3] Spector, L., 2012. Assessment of problem modality by differential performance of lexicase selection in genetic programming. *Proceedings of the fourteenth international conference on Genetic and evolutionary computation conference companion - GECCO Companion 12*.

[4] Cava, W.L., Spector, L. & Danai, K., 2016. Epsilon-Lexicase Selection for Regression. *Proceedings of the 2016 on Genetic and Evolutionary Computation Conference - GECCO 16*.

[5] Spector, L., 2001. Autoconstructive Evolution: Push, PushGP, and Pushpop Proceedings of the Genetic and Evolutionary Computation Conference

[6] Pantridge, E. & Spector, L., 2017. PyshGP. *Proceedings of the Genetic and Evolutionary Computation Conference Companion on - GECCO 17*.

[7] Brameier, M., 2005. On Linear Genetic Programming. (maybe extra and another citation here)

[8] Spector, L., 2003. *Push 3.0 Programming Language Description*. Available at: http://faculty.hampshire.edu/lspector/push3-description.html [Accessed November 13, 2019].

[9] Spector, L., Klein, J. & Keijzer, M., 2005. The Push3 execution stack and the evolution of control. *Proceedings of the 2005 conference on Genetic and evolutionary computation - GECCO 05*.

[10] Pratihar, D., 2003. Evolutionary Robotics. *SpringerReference*.

[11] Ferreira, C. et al., 2014. Genetic Programming Applied to Biped Locomotion Control with Sensory Information. *Proceedings of the 11th International Conference on Informatics in Control, Automation and Robotics*.

[12] Silva, P. et al., 2014. Automatic generation of biped locomotion controllers using genetic programming. *Robotics and Autonomous Systems*, 62(10), pp.1531–1548.

[13] Olivier, M., Cyberbotics Ltd. Webots™: Professional Mobile Robot. Available at: https://journals.sagepub.com/doi/full/10.5772/5618 [Accessed November 13, 2019].

[14] Hohl, L. et al., 2006. Aibo and Webots: Simulation, wireless remote control and controller transfer. *Robotics and Autonomous Systems*, 54(6), pp.472–485.

[15] Wolff, K. & Nordin, P., 2003. Learning Biped Locomotion from First Principles on a Simulated Humanoid Robot Using Linear Genetic Programming. *Genetic and Evolutionary Computation — GECCO 2003 Lecture Notes in Computer Science*, pp.495–506.

[16] Lee, W.-P., Hallam, J. & Lund, H., 1997. Applying genetic programming to evolve behaviour primitives and arbitrators for mobile robots. *Proceedings of 1997 IEEE International Conference on Evolutionary Computation (ICEC 97)*.

[17] Baeck, T., Fogel, D., Michalewicz, Z. 2017. *EVOLUTIONARY COMPUTATION 1: basic algorithms and operators*, Place of publication not identified: CRC Press.

[18] Holland, J.H., 1973. Genetic Algorithms and the Optimal Allocation of Trials. *SIAM Journal on Computing*, 2(2), pp.88–105.

[19] Koza, J.R., 1992. *Genetic programming: on the programming of computers by means of natural selection*, Cambridge, MA: MIT Press.

[20] Poli R., Langdon W.B. (1998) Genetic Programming with One-Point Crossover. In: Chawdhry P.K., Roy R., Pant R.K. (eds) Soft Computing in Engineering Design and Manufacturing. Springer, London

[21] Helmuth, T. et al., 2018. Linear Genomes for Structured Programs. *Genetic and Evolutionary Computation Genetic Programming Theory and Practice XIV*, pp.85–100.

[22] Pitonakova L., Giuliani M., Pipe A., Winfield A. (2018) Feature and Performance Comparison of the V-REP, Gazebo and ARGoS Robot Simulators. In: Giuliani M., Assaf T., Giannaccini M. (eds) Towards Autonomous Robotic Systems. TAROS 2018. Lecture Notes in Computer Science, vol 10965. Springer, Cham

[23] Microsoft, *User Guide*. Available at: https://msdn.microsoft.com/en-us/library/dd936006.aspx [Accessed November 17, 2019].

[24] Robot Virtual Worlds: ROBOTC: VEX & NXT Simulator. *Robot Virtual Worlds | ROBOTC | VEX & NXT Simulator*. Available at: http://www.robotvirtualworlds.com/rvwtools/ [Accessed November 17, 2019].

[25] Osrf, Why Gazebo? *Gazebo*. Available at: http://gazebosim.org/ [Accessed November 17, 2019].

[26] Kala, R., 2012. Multi-robot path planning using co-evolutionary genetic programming. *Expert Systems with Applications*, 39(3), pp.3817–3831.

[27] Lazarus, C. and Hu, H., 2001, April. Using genetic programming to evolve robot behaviours. In *Proceedings of the 3rd British Conference on Autonomous Mobile Robotics & Autonomous Systems* (Vol. 5).

[28] Perez, A.L.F., Bittencourt, G. & Roisenberg, M., 2008. Embodied Evolution with a New Genetic Programming Variation Algorithm. *Fourth International Conference on Autonomic and Autonomous Systems (ICAS08)*.

[29] Sharabi, S. & Sipper, M., 2006, GP-Sumo: Using genetic programming to evolve sumobots. *Genetic Programming and Evolvable Machines*, 7(3), pp.211–230.

[30] Spector, L. & Robinson, A., 2002, Genetic Programming and Evolvable Machines 3: 7. <https://doi.org/10.1023/A:1014538503543>

[31] Dabhi, V.K. & Chaudhary, S., 2014. Empirical modeling using genetic programming: a survey of issues and approaches. *Natural Computing*, 14(2), pp.303–330.