THE UNIVERSITY OF NEW SOUTH WALES
THE SCHOOL OF COMPUTER SCIENCE AND ENGINEERING

Dynamic Omnidirectional Kicks on Humanoid Robots

By: Belinda Teh
tehbelinda@cse.unsw.edu.au

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Supervisors: Bernhard Hengst and Maurice Pagnucco
Assessor: Claude Sammut

Abstract

One of the challenges of humanoid robot soccer is being able to kick balls and score goals as quickly and accurately as possible. As such, the purpose of this thesis was to create a more efficient kick and apply it in a robot behaviour. The following report thus documents the improvements made to rUNSWift's entry in the Robocup Standard Platform League of 2012. First, the developments in kinematics to achieve a greater sense of balance and accuracy within the body model are presented, which proved useful to many other rUNSWift modules such as vision and localisation. Next, a dynamic omnidirectional kick was created within the kick engine with the attributes of power, accuracy, and reliability to combat slow line up and reaction times. This was supplemented by the speedy and manoeuvrable dribble kicks integrated into the walk engine, which proved useful for retaining ball possession even with other competing robots nearby. Methods of arm swings in the front getup routines are also discussed to combat the large number of falls that can occur as a result of multiple robots competing for the ball. Finally, these efforts were combined into a striker behaviour based on state machines and decision trees, which showed significant speed increases over strikers from previous years. The team performed well at the Robocup competition with the striker scoring the most goals out of all the teams, and rUNSWift achieving third place overall.

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Chapter 1

Introduction

1.1 Motivation

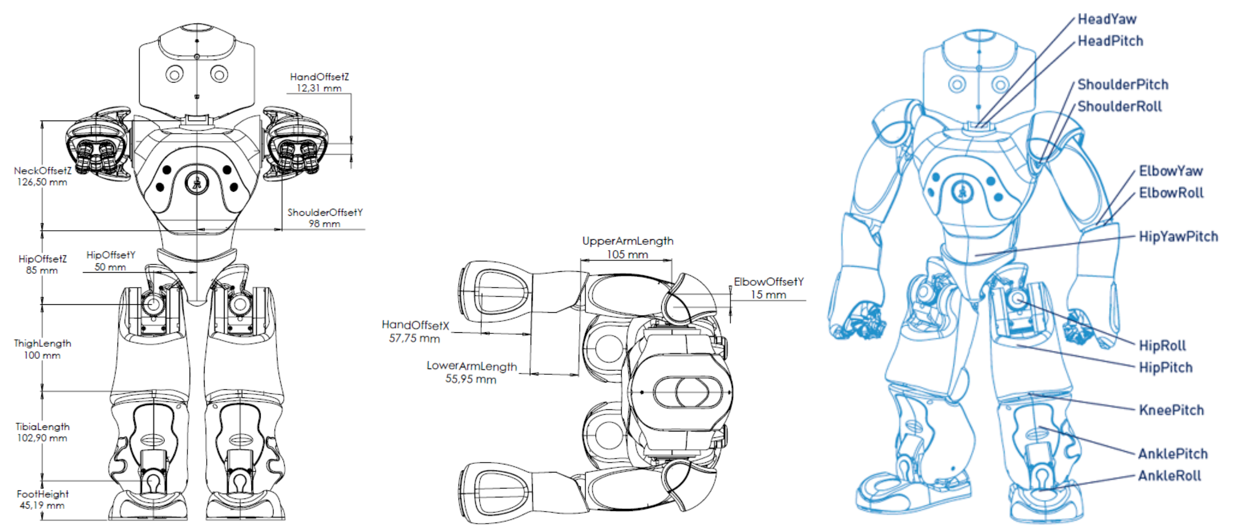
In order to win a soccer match, one must first be able to keep the ball away from opponents and then be able to score. As such, being able to dribble and kick a ball into the goals is critical to the success of any team. More importantly, the faster and more versatile the kick, the higher the chances of scoring before the other team. These issues of speed, accuracy and reliability are becoming an increasing focus in the Robocup Standard Platform League [1], especially with the advancements in the Aldebaran Naos [2] and increased game pace.

Robocup[1] is an international robotics competition aimed at promoting research of artificial intelligence through soccer matches. Ultimately, the goal is to create a team of autonomous humanoid soccer players that can compete against the human champions of the World Cup. While the competition has since expanded to many other leagues, the application of this thesis is in the Standard Platform League (SPL). The main focus of this league is on the software behind autonomous soccer playing robots as opposed to the hardware, as all teams use the Aldebaran Nao as the common robot platform.

A common approach to scoring in current Robocup SPL matches is to position the striker robot facing forward on the straight line formed by the ball and the goal before kicking the ball with the front of the foot. Unfortunately, this method is limited by its inflexibility and slow speed as the ideal position might not always be available or difficult to achieve. Humans on the other hand, are able to control the ball accurately, quickly and reliably in multiple directions on the fly. If we could emulate this behaviour in the Aldebaran Naos, the chances of scoring fast goals and dominating the competition would be greatly improved.

[1]`http://www.robocup.org/`

Figure 1.1 Schematic of the Aldebaran Nao



1.1.1 Balance

An important underlying aspect to kicking is first achieving a greater understanding of the body model to remain balanced. With 21 degrees of freedom, coordinating the Nao's movement for locomotive tasks can become complicated. Studying the mechanics linking all 21 joints and modelling this kinematics chain with all its constraints is thus particularly important. Without an accurate kinematics model and centre of mass, making adjustments while standing on a single support foot can be quite a challenge. Unless the appropriate counter balances can be determined, lifting a foot to kick would not even be possible.

1.1.2 Accuracy

There needs to be a certain degree of control and accuracy to a kick, especially since missing the goal and causing the ball to go out would consequently hand the advantage over to the other team. Currently, the robot's pose is determined by the kinematic links from the cameras in the robot's head to the point touching the ground on the robot's foot. The calculation of its stance can then be used to compute ground distances and orientations of objects seen in camera frames. Thus by improving the accuracy of kinematics and the body model, the robot's sense of the world around it will be improved, resulting in more accurate localisation. This added benefit means that the ball can also be pinpointed more precisely, allowing for more accurate foot contact when kicking.

1.1.3 Speed

No matter how intricate or accurate the kick might be, it would be of no use if an opponent robot managed to clear the ball first. As such, speed is integral to the creation of an omnidirectional kick. This calls for improvements not only in preparation times for kicks and actual kick durations, but also in the integration between walking and kicking.

1.1.4 Reliability

Due to the unexpected and external influences that can happen during games, it is crucial that a certain level of flexibility and reliability be obtained. The kick needs to be able to adapt to events such as the ball being knocked around slightly or getting pushed by another robot in the middle of a kick, which can happen a lot in tussles for the ball. With a dynamic kick that can clear a ball even in critical situations, the striker robot would be better equipped to score goals despite tough competition.

1.1.5 Striker

Incorporating these advances into striker behaviour was a huge motivation for rUNSWift 2012 as it addressed one of the big issues in previous competitions. Even though the team's robots often managed to walk to the ball first, a lot of time would then be wasted in lining up and performing the actual kick. This pause would typically allow enough time for an opponent robot to dribble the ball away, or at least get into a position to block the goal. Hence with the addition of a dynamic omnidirectional kick, the team would gain a significant advantage in soccer matches.

Apart from walking and kicking, static movements, which are simply defined using a sequence of joint values, are also required during competition. A particular example is the getup routine, which the striker is often subject to as falling robots tend to occur as a result of robots clashing to get to the ball. As such, important considerations must also be made for balance, speed and reliability in these routines. Balancing is required to enable the robot to stand back up on its feet, while speed is important for getting the robot back into the game as quickly as possible, and finally reliability is needed to ensure its ability to get up in all sorts of situations.

1.2 Aims

The aims of this thesis can be summarised into the following three areas:

- Incorporate mass and lean into kinematics chain calculations to improve balancing and recovery as well as the accuracy of vision and localisation estimations.
- Develop a dynamic and omnidirectional kick that is both fast and powerful while remaining balanced.
- Implement a striker behaviour for Robocup Standard Platform League matches with improved line up and kick times.

1.3 Outline

Chapter 2: describes related work in the balancing of humanoid robots and dynamic kicking as well as the background of rUNSWift's previous strategies.

Chapter 3: encompasses the mass and lean related additions in the kinematics system and evaluates their effectiveness.

Chapter 4: explains the methods behind developing an omnidirectional kick, as well as the improvements in the kick engine, and presents the resulting findings.

Chapter 5: discusses the approach behind developing increasingly integrated dribbles within the walk and dribble kick engines.

Chapter 6: analyses the methods used when programming set actions, in particular the front getup routines, and discusses how effective they are.

Chapter 7: describes the mechanics of rUNSWift 2012's striker behaviour including the underlying state machine and decision tree, and discusses its performance.

Chapter 8: offers suggestions for future development in the areas related to kinematics, motion and behaviour.

Chapter 9: concludes and summarises the findings of this report.

Chapter 2

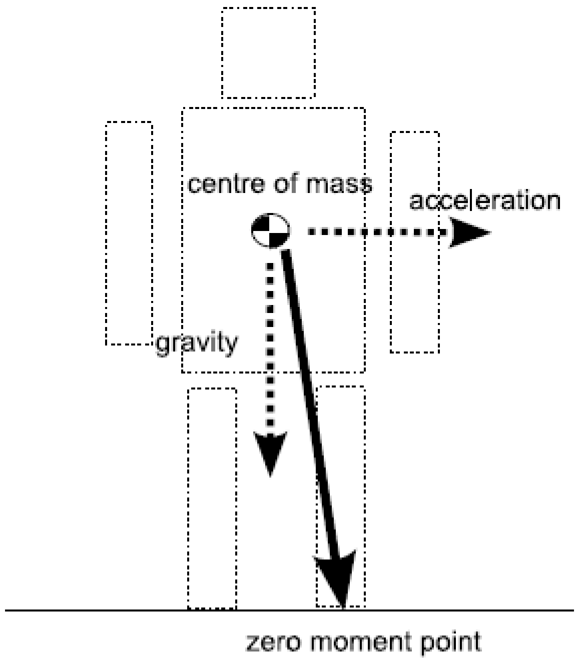
Background

2.1 Locomotion and Balancing

2.1.1 Centre of Mass

Balancing has long been a challenge in humanoid locomotion, with active stabilisation in particular becoming a growing concern. Popular methods have involved the learning of joint movements to control the robot's centre of mass and zero moment point (ZMP) as shown in Figure 2.1, as well as the application of human-like fall avoidance strategies [3–5].

Figure 2.1 Relationship between the centre of mass and the zero moment point [6]

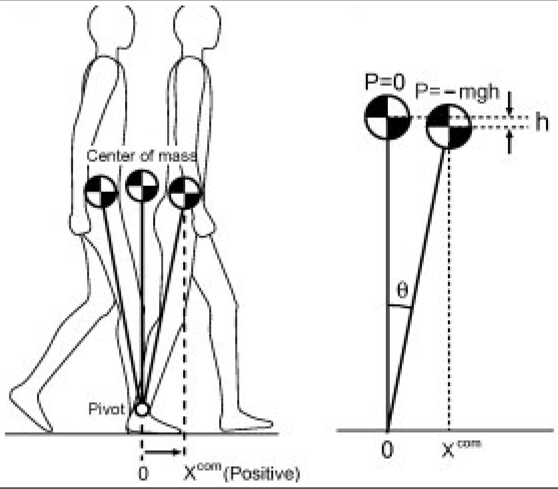


The ZMP is defined as the point on the ground where all acting forces equate to zero, in other words, no more movement would be produced. The centre of mass is defined as the average location of within a group of solids as weighted by each of their respective masses. It is calculated as follows, where x_i and m_i refer to the location and mass of each individual solid and M is the total mass.

$$CoM = \frac{1}{M}\sum m_i x_i$$

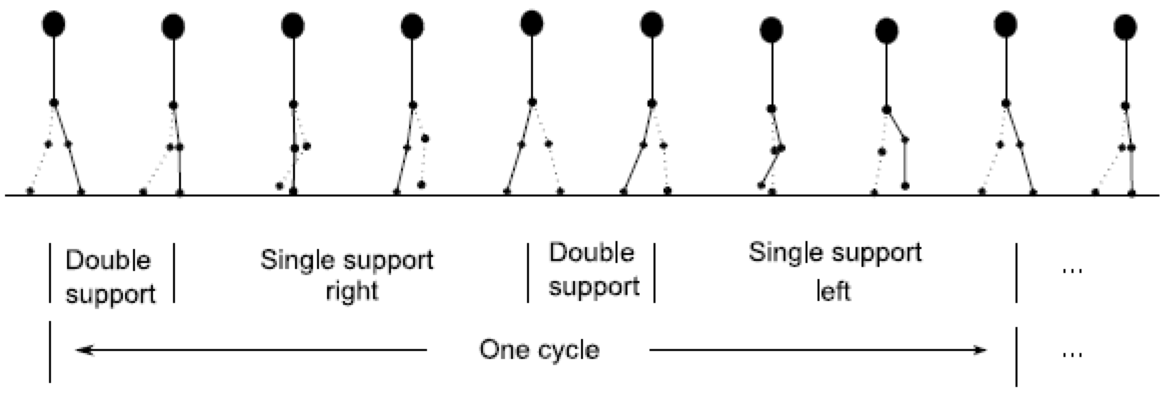
However, due to the cost and manufacturing limits in hardware on commercially available humanoid robots, not all balancing options are always feasible. Notable recent approaches include the development of a full body push recovery controller on the DARwin-OP [7]. Inspired by the human reflex of using our ankles, hips, and stepping to regain balance, the three biomechanically motivated push recovery strategies were written. By applying controlled pushes upon the robot through the use of a motorised moving platform, hierarchical controller parameters to integrate both the walk and the recovery strategies were reinforcement learnt [8] on the robot itself. Their experiments proved successful, demonstrating that despite the lack of specialised hardware, recovery from external influences, even while moving in different directions, was possible.

Figure 2.2 Inverted pendulum model and its potential energy, with the body's centre of mass as the swinging point mass of the pendulum



In terms of the Standard Platform League, teams such as B-Human from the University of Bremen have done some similar work on balancing the Aldebaran Naos [9]. An inverted pendulum as shown in Figure 2.2 was used to model the Nao, and the motion of the centre of mass was tracked according to its position and velocity relative to the origin of the pendulum [10]. With dynamic adjustment of the walk's support phases (see Figure 2.3), the pendulum aimed to keep its origin in the optimal position beneath the centre of the feet and the centre of mass at an ideal movement for the next leg swing. To compensate for hardware inaccuracies and external forces, sensory feedback was also integrated. By observing the differences between the desired centre of mass and the recorded centre mass, appropriate adjustments could be made to reduce the error. Finally, iterative inverse kinematics was used to calculate the relevant joint angles for achieving the required centre of mass position [11]. Further improvements were made in 2011, in particular to the dynamic handling of external influences. Rather than simply performing one counter action to return the centre of mass to its ideal position once a disturbance had occurred, the whole trajectory was modified to continue along with the disturbance and would be continually adjusted for stability [12]. With these features, B-Human managed to create a speedy yet robust walk which was a contributing factor to their first place championship.

Figure 2.3 Support phases during a bipedal walk cycle [6]



2.1.2 Kicking

Besides its application in walks, the centre of mass has many uses in motion engines in general, in particular for kicking. The common and underlying methods to all these different movements, whether it be walking or kicking, is to keep the ZMP and centre of mass within the support polygon of the foot and at a stable velocity in order to remain upright. A kick is conventionally carried out as a defined set of motion sequences by interpolating between key points, and the majority of SPL teams have adopted this type of approach [13–16]. However without dynamic reactive strategies, these hardcoded movements would be unable to handle any external disturbances. For example, updates in the ball position, nudges from another robot or existing sways while transitioning from walking could cause such a kick to fail.

B-Human 2011 have instead moved to a dynamic approach which defines the kick motion as a set of Bezier curves that can be adjusted online [17]. The control points of each curve are dynamic and decided at the start of each kick phase, allowing the foot to adjust to the current ball position. The final control points can be further transformed to rotate according to direction parameters from behaviour, permitting switches between forward and side kicks.

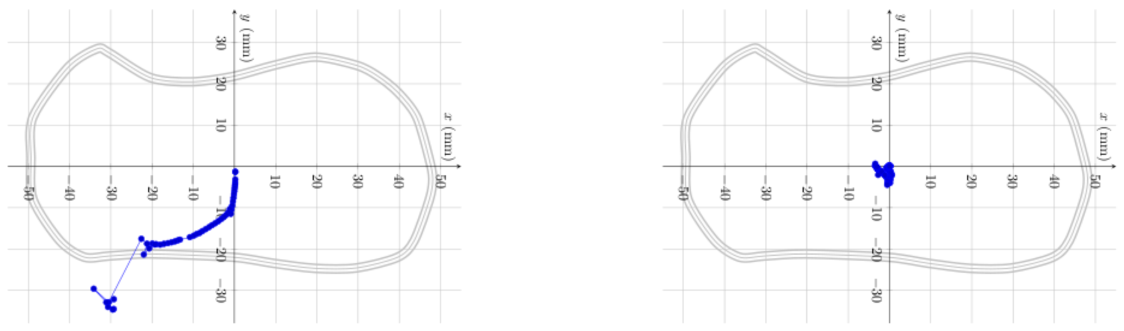
In terms of balancing, the centre of mass is projected to the ground and its desired position is calculated by computing the harmonic mean of future positions of the support foot, allowing it to adapt in preparation. Differences between the projected and measured centre of mass are used as input into a PID controller for the robot's tilt angle. The resulting values are then transformed into rotation angles using the estimation of the height of the centre of mass with Pythagoras' Theorem. However, B-Human discovered that balancing using the centre of mass alone was not sufficient, so an additional controller was added to further compensate for unexpected disturbances. Angular velocity as measured from the gyroscopes is distinguished from velocity introduced by disturbance compensation as opposed to actual desired velocity. The error between the two is then fed into a PID controller, which provides offset angles for balancing via the hip pitch and hip roll joints.

To test the effectiveness of the balancing controllers, a 500g weighted pendulum was swung into the back of a robot at a height of 35cm while it was standing on one leg [17]. Ten trials without the controllers in action resulted in the robot falling down every time. In comparison, the balancing robot was able to recover in around 2.5 seconds for all ten trials. With this kick, the deviation in angular accuracy was $3.32°$ on average, with the ball typically reaching a distance of 5 to 6 metres. Once again, B-Human were clearly successful, obtaining first place during Robocup 2011 with one of the most powerful and accurate kicks in the competition. Although the direction was limited to forward or side kicks, their line up placement and walk integration was sufficient enough that additional directions were not particularly necessary.

Humboldt is another SPL team that left the key frame technique behind in favour of using adaptive motion control to create a dynamic kick [18]. Their kick was split into four phases: preparation to shift the robot's weight, retraction to pull the foot back, execution to perform the kick and wrap-up to return the foot to the ground. If any external influences occurred that meant carrying out the kick was no longer possible, the robot would be able to jump straight to the wrap-up phase. Dynamic adaptation was introduced in the retraction phase, which made use of visual input to adjust the foot position before executing the kick. The Nao's foot was assumed to be round like a ball in order to simplify the modelling of the collision between the two. Given a kick direction, the ideal point of collision could then be calculated. Their next step was to generate the reachable space of the kicking foot based on physical experiments on the robot, and together with the collision point, plan the motion trajectory of the kick. The retraction point should be as far as possible from the collision point for maximal impact, however angle and distance to the ball requirements must also be met. Instead of using the fastest reachable path to the point, the shortest one was used to prevent unwanted collisions, for example with the ground, with adjustments according to the reachability grid. A prediction of the resultant kick movement was then compared to the requested direction, and the precision of the match was used to decide whether the kick should be executed or not.

All these kicking phases were also subject to the balancing strategy of keeping the centre of mass in the centre of the support polygon as shown in Figure 2.4. Sensor data was used to calculate the centre of mass and the support polygon, then a P controller was used to adjust the inclination of the robot's body such that the difference between the two was minimised. Since the leg pose and hip position were already set by the reachable trajectory, only the body inclination, or lean, was dynamically adjusted.

Figure 2.4 Centre of mass movement relative to the support polygon as a Nao transfers its weight to a single foot without stabilisation (left) as opposed to with stabilisation (right) [18]



The experiments to test these were broken down into two areas - adaptivity of direction and adaptivity of ball position [18]. First, the kick was set to a direction of 0° and incremented at an angle of 10° up until 90°. They found that there was a negative offset in all the trials with the largest errors at 20°, which could be explained by inaccuracies in their assumptions such as the foot being round like a circle. In general though, the error in the resultant direction remained less than 10° for kick directions less than 20° with a maximal distance of around 3 metres, and between 10-20° for the rest, reaching distances up to 1 metre. The second experiment involved kicking straight while changing the position of the ball randomly within a 25x20cm rectangle. Most of the 100 kicks reached distances between 1 and 2.8 metres, though kick positions past 10cm in either direction tended to lose their accuracy. Finally, it should be noted that the robot was able to balance on one foot and adjust dynamically to the different ball positions and directions during the experiments.[1] While Humboldt's

[1]See video example of experiments at `http://www.informatik.hu-berlin.de/~naoth/media/video/dynamic_kick.mp4`

dynamic balancing and omnidirectional ability were impressive, the lack of power and speed in their kicks brought down their competitive potential.

There is also the question of what is the best and most efficient way to perform a kick. In 2010, Hausknecht and Stone decided to apply machine learning, which had typically already been used for walking and in simulation, to the task of kicking on a real robot - a Sony Aibo [19]. Parameters for the kick were simply raw joint angles, with the learning space reduced by taking advantage of the Aibo's symmetry. These were then learnt using Hill Climbing and Policy Gradient algorithms over 860 kicks up an inclined ramp. The ramp's height, and hence slope, was adjusted such that the robot would be unable to kick the ball off the end. Some human input was required to feed the result back to the robot, namely the distance of the kicked ball and the time it took for the ball to be kicked then return to the robot, and to reposition the robot for the next kick. On average, the learned kick managed to move a ball 373.66cm, about 50cm more than one of Robocup's top kicks with about 30cm less in standard deviation and a maximal distance of 628cm. However, this was at a sideways loss of accuracy of about 4cm per metre, which was not too significant, but was likely due to power and distance being emphasised during the learning process instead.

Since passing was key amongst the Aibo League, it was also important that the kick be controllable and predictable. By varying the amount of time spent in the kicking phase, they managed to gather data of the ball distance according to kick frames, which could then be modelled using a quadratic function. It was found that within a range of 60-400cm, the learned kick was accurate to within 45.5cm on average. Considering this distance is within 1-2 Aibo lengths, using this method to create a variable distance kick was useful, though perhaps learning for this specific task could further improve accuracy. Apart from being successful at producing a more powerful kick than Robocup's top teams through machine learning, their methods had also saved developers the painstaking time taken to manually tune such parameters. However, this was only applied to the Sony Aibo which has a much simpler joint configuration than the Aldebaran Nao, though many of the concepts in learning could still be ported over.

Now that the robots in use in the soccer leagues are beginning to resemble humans more and more, the notion of biomechanics is becoming increasingly valuable when programming humanoid robots. By modelling the human body with 34 degrees of freedom in a motion capture and analysis tool, a team from Japan experimented with the manipulability and joint-torque properties of a human as they performed a kick [20]. The key results they found were that both the lower and upper torsos were equally important in kicking, as the rotational energy transmitted between the two is crucial in the kicking motion. Combined with the manipulability of the kicking leg and shorter periods, the eventual velocity on impact with the ball could be maximised. As mentioned earlier, biomechanics has already begun to be applied in walking. While the Naos are still far off from having the same manoeuvrability as humans, there are still some concepts worth noting for kicking, such as rotation in the upper torso, that show future promise.

2.1.3 rUNSWift

Originally, in the transition from 4-legged Sony Aibos to the Naos, rUNSWift 2008 calculated the centre of mass and integrated it into their walk balancing [21]. However since Aldebaran did not provide the precise centre of mass for each link in the robot, several assumptions had to be made, causing a loss of accuracy in the calculated centre of mass. Kicks were created by specifying set parameters such as time period and joint angles across different kick phases. The centre of mass was also applied in kicks for additional stability, but unfortunately, the Power Kick developed never managed to be utilised in an actual game due to behavioural issues.

In addition to the Power Kick from 2008, a new kick, known as the Bunt Kick, was created in 2009 [22]. Joint poses were captured and played back using an action creation system until a satisfactory sequence was found. While the ball would not be kicked quite as far, the total execution time taken was 4s as opposed to 9s for the Power Kick. Unfortunately due to behavioural decisions, it too was not used in actual games that year. It was at this point that Tay discovered that the asymmetry present in the Naos, which meant that simply mirroring the joint poses for left and right kicks was unsuccessful, and tweaks had to be made to properly balance both sides while walking.

During 2010, existing systems were overhauled and a brand new rUNSWift architecture was implemented [16]. One of the new developments involved using the foot sensors and accelerometers to determine the centre of pressure. This was used in the creation of a walk (named FastWalk) to apply feedback control and retain balance. While the centre of mass was not included, FastWalk was useful for its purposes - to walk fast in a relatively straight line, and became one of the signatures of the rUNSWift team. However, it was too unstable on single support phase, so an alternative had to be used when transitioning into kicks. A second walk was also in development (named SlowWalk), which was used as the intermediary. The SlowWalk motion was used to rock the robot back and forth between a single support foot, while the swing foot executed the kick by following a series of sinusoidal joint trajectories. Forward, side and back kicks were created to expand the reach of the robot's kicks, though only the first two were used in competition. Considering rUNSWift 2010 placed second in the world, the new ground set by the team had proved worthwhile.

An attempt was made at an omnidirectional kick in a separate Kick Generator, as opposed to the Action or Walk Generators like the previous work [16]. A state-based model was used with 6 states as follows:

1. Lean: The robot shifts its weight on to the support foot.
2. Lift: The free leg is lifted into the air.
3. Line-up: The leg is dynamically lined up to the position of the ball along the robot's coronal axis. If kicking at an angle, the leg also rotates using the robot's pelvis joint, known as the HipYawPitch joint.
4. Kick: The swing of the kick is dynamically executed to connect the tip of the foot to the ball at the appropriate position and direction.
5. Un-line-up: The robot returns the leg to a neutral position, still off the ground.
6. Un-lean: The robot shifts its weight back to both feet and lowers its kicking foot.

This omnidirectional kick was able to extend its reach by 5cm in front of the foot and 12cm to the side of the centre of the robot, which would be approximately 7.5cm from the side of the centre of the foot. However it seemed that it was unable to correctly calculate the offset in its foot position relative to the ball, as 45° kicks were typically offset by 3cm. This could have been due to a number of reasons, such as inaccuracies in the ball filter or discrepancies in the kinematics used to calculate the position. Unfortunately due to it's incomplete omnidirectionality, slow execution time, and weaker power even in its forward kicks with a maximal distance of 4 metres, it was eventually scrapped.

By 2011, the walk had been restructured, though the notion of having a slow conservative walk and a fast aggressive walk still remained. The main balancing issue remaining was the walk's slow ramp up period, as finding an appropriate hip rock to create a smooth walking motion was unsuccessful. Further developments had been made in balancing though, notably White's Open Challenge in step and ankle placement using reinforcement learning [23]. The robot was modelled using an inverted pendulum with the help of kinematic information, the on-board IMU (Inertial Measurement Unit) and a simple Kalman Filter to track its states. Ankle balancing control was applied by using the ZMP to determine the location of pressure on the foot and applying the appropriate rotations if necessary. Step control simply involved altering the walk cycle to place the foot directly at the position requested by the Reinforcement Learning Planner. Though these methods enabled a robot to reliably handle obstacles twice as high as compared to a robot without them, and the demonstration placed 3rd in Robocup 2011's Open Challenge, it was not made ready for competition.

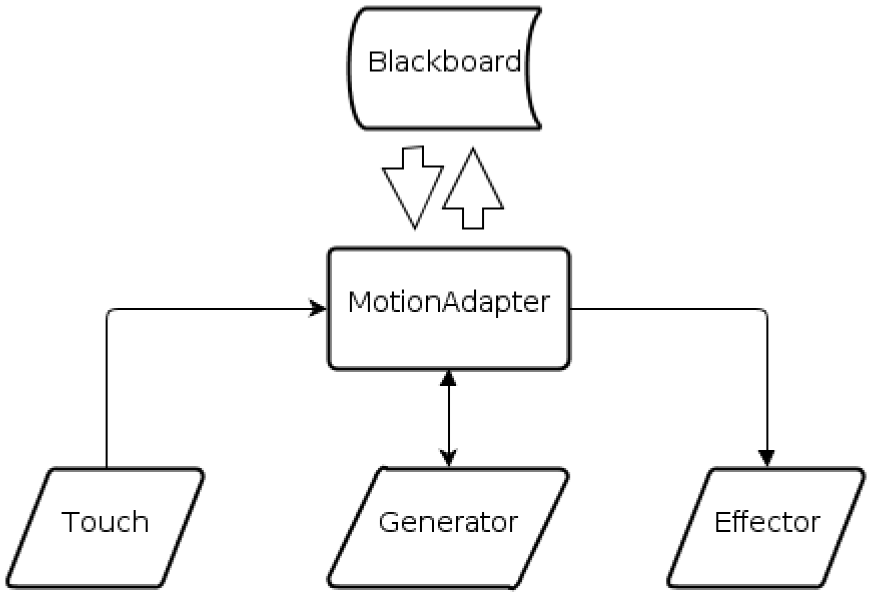
In terms of kicks, one of the significant improvements was the incorporation of the kick engine into the walk engine for smoother and faster transitions [23]. Standard kicks were similar to previous years, with both forward and side kicks being defined by a sequence of interpolated sinusoidal trajectories. Including a weight transfer time of 4.5s, at maximum power their execution times were 6.7s and 7.8s respectively. On the left and right foot, the side kick managed a range of 1.14-1.78m and 1.46-2.16m respectively, while the forward kick managed a range of 5.1-6.5m and 2.54-2.91m respectively. The significant deficiency in the right forward kick despite the mirrored kick motions can be attributed to the motors in the right leg not being able to keep up to the speed of a full swing, reflecting the asymmetry of the Naos. Dribble kicks were also developed to quickly move the ball short distances which could be executed within a walk cycle with a period of 1.4s. On the left and right foot, the side dribble managed a range of 0.49-0.75m and 0.65-1.29m respectively, while the forward dribble managed a range of 0.59-0.91m and 0.44-0.7m respectively. Once again, large differences in the side dribbles reflect the differences in strength of the left and right hip joints in the Naos. While a third kind of kick, known as the shuffle kick, was also attempted in order to dribble and move with the ball, it was too unstable to be used. As such, dribble kicks were used rather effectively in tussle situations against enemy robots while mainly left forward kicks were used for big goal shots, which were some of the most powerful in the competition as even the goalie could potentially score goals from the far end of the field.

With the advent of the Nao v4s in 2012, many improvements were made possible. In terms of locomotion, the advances in the IMU and gyroscopes meant that the body lean could be estimated more accurately. While Liu had begun to apply these additions to the walk [24], there were also applications for body lean in kicks. Not only could it be used for dynamic balancing during kicks, but for improving the robot's estimate of its kinematics, indirectly increasing the accuracy of localisation and foot positioning for kicks. The desire to create a new walk for 2012 with less stress on the motors and improved smoothness led to a greater need of the proper calculation of the centre of mass. By tracking its position and velocity, it could be used to help control walk cycles and improve balancing in general. This was also now possible due to updates in Aldebaran documentation specifying the exact dimensions and locations of each link and their respective centre of masses. Improvements in motors also meant that the robots should be capable of moving their joints faster, more accurately and with more power. One of the major issues in 2011 was the speed of the striker's line up and kick, which could be addressed by making the whole process faster and more versatile. Hence, this project was begun to address the need to improve issues in balancing, create an omnidirectional kick and ultimately develop a new striker that would be able to score goals quickly and efficiently.

2.2 Overview of rUNSWift Motion Architecture

Current motion architecture is based on the original rewrite of rUNSWift 2010 [16] and built upon by White in 2011 [23]. The motion module is run in its own thread with the highest priority on the robot, as joint angles need to be calculated at 100 frames per second to maintain stability. The MotionAdapter class controls this thread and is the first entry point for receiving robot data, such as an ActionCommand from a behaviour request. This data would have originated from the Blackboard, a common data structure that all rUNSWift modules use to share information.

Figure 2.5 Overview of basis of motion architecture



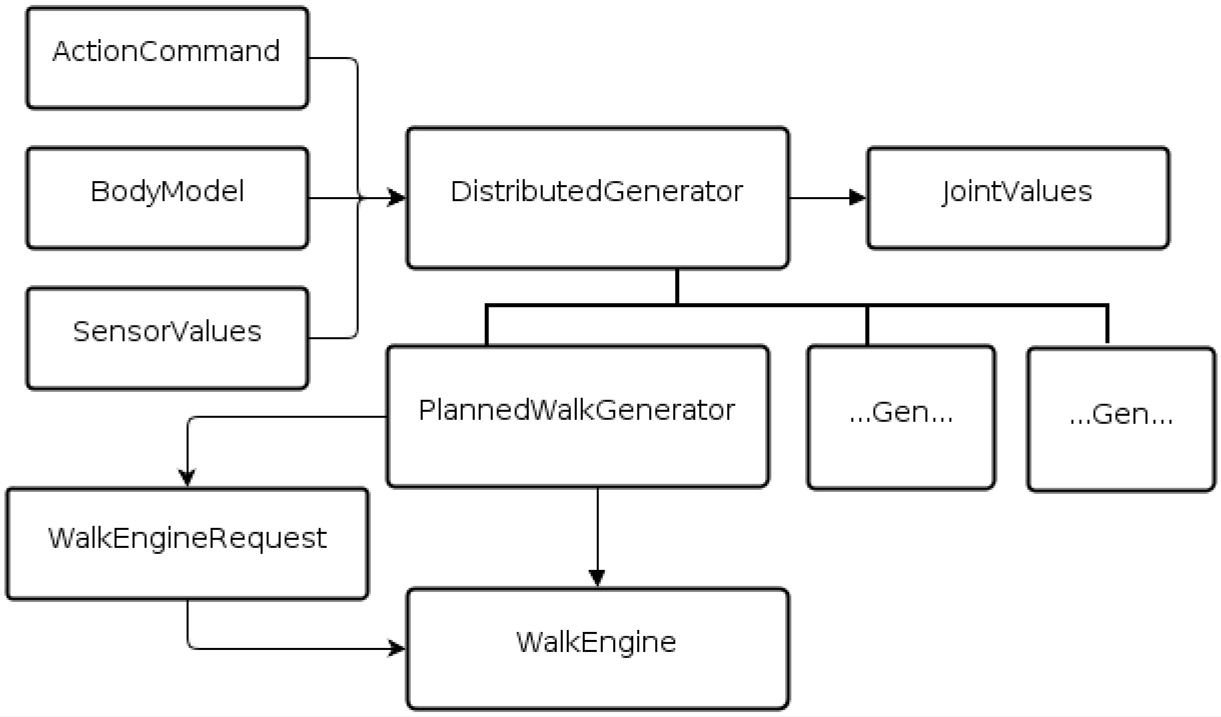
It then calls upon its three children objects in turn:

- **Touch** - receives and filters input from the Nao's sensors.
- **Generator** - processes the behaviour request and sensor input to generate appropriate joint values and subsequent odometry.
- **Effector** - uses generated joint values to output robot action.

Once the cycle is complete, data such as odometry, sensor values and current action are passed back to the Blackboard for use in other modules.

There is one main generator class, the DistributedGenerator, that calls upon subsequent generators depending on the requested action. Focus will be mostly applied to the development within the PlannedWalkGenerator and its related objects as it is the handler for all walk, kick and dribble actions.

Figure 2.6 Walk, kick and dribble generator architecture



ActionCommand: contains a collection of data types (Body, Head and LEDs) to communicate parameters set by the Behaviour module.

BodyModel: contains the inverted pendulum model and relevant kinematics data, such as the ZMP.

JointValues: contains a value for each of the robot's joints which will be passed to an Effector object.

PlannedWalkGenerator: plans out high level steps for the walk depending on the requested ActionCommand while ensuring that it remains synchronised with the current state of the body model and sensor values.

SensorValues: received from a Touch object with current values from each of the robot's sensors and joints.

WalkEngineRequest: data structure constructed by PlannedWalkGenerator for storing information based on the behaviour request.

WalkEngine: uses body model, sensor data and the WalkEngineRequest passed in to handle lower level details of the walk and generate walk cycles. It also transitions in and out of the integrated kick engine to execute kicks and dribbles depending on the WalkEngineRequest's parameters. It is this class that actually constructs the data for setting the JointValues.

Chapter 3

Kinematics

One of the first steps towards enhancing the motion module was to improve the body model and kinematics of the robot. A more accurate kinematics model would allow for quick responses to any disturbances and finer control over the robot's movement, producing more effective walking and kicking techniques. Another particular application of kinematics is the calculation of the chain between the camera in the head and the foot on the ground in order to create the Pose and keep track of the robot's current stance.

The Pose object is instrumental in the rUNSWift pipeline as it is used to construct the horizon, which is defined as the line parallel to the y-axis of the robot and at an infinite distance away. It is particularly useful for vision algorithms as it can help place constraints on the position of certain objects, for example, it should not be possible for a ball or any part of the field to appear above the horizon. Pose is also responsible for converting camera coordinates of objects seen in vision into field coordinates that are relevant to localisation and behaviour. For example, depending on the location of projected field points, they could be classified into groups to form key features such as corners or the centre circle [25].

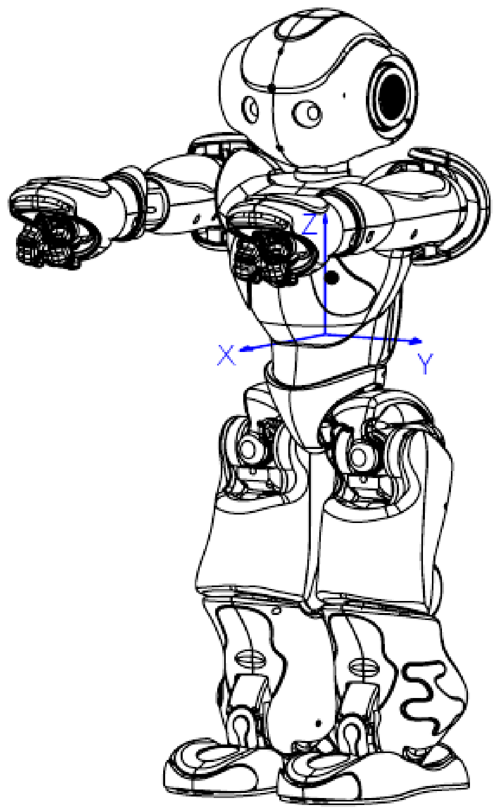
Due to its links to the Pose and the related vision and localisation modules, the kinematics calculations were originally carried out as part of the Perception thread [16]. However, to keep up to date with its use in the Motion thread, which was run 100 times a second as opposed to 30, it was accordingly shifted over. A slight lag was introduced to compensate for the difference in cycles between the two threads. Along with newly available information on the Nao v4s, such as the improved IMU and hardware documentation from Aldebaran, many areas could benefit from these updates.

3.1 Centre of Mass

A robot's centre of mass can provide a lot of information about its current state of balance, and has proven useful in many dynamic balancing, walking and kicking techniques as discussed in Chapter 2. Aldebaran documentation [26] provided the mass and centre of mass of each of the solids that compose the Nao relative to the zero posture (see Figure 3.1), and from these it was possible to derive the robot's centre of mass at each cycle. The Denavit-Hartenburg (DH) convention [27] was applied to determine the positions and masses of each of the solids relative to the torso's frame of reference. Tables 3.1-3.3 describe the DH parameters used for the right side of the body, with the left being symmetrical. Note that some lines could be further condensed if only relative positioning was required, but are left in such a form so that the mass can be determined in each joint's frame of reference before continuing the transforms down the chain.

For more practical uses of the centre of mass, it would be converted into the foot's or the ground's frame of reference for walking and balancing, with body lean taken into account.

Figure 3.1 The Nao's 'Zero Posture' and frame of reference



Joint Frame	a	α	d	θ
Head Yaw	0	0	neckOffsetZ	Cy
Head Pitch	0	$-\pi/2$	0	Cp
Torso	0	$\pi/2$	0	0

Table 3.1: DH Parameters used between head and torso

Joint Frame	a	α	d	θ
	0	0	shoulderOffsetZ	0
	0	$\pi/2$	shoulderOffsetY	0
R Shoulder Pitch	0	$-\pi$	0	Sp
	0	$\pi/2$	0	0
R Shoulder Roll	0	0	0	Sr
	upperArmLength	0	0	0
	0	$-\pi/2$	-elbowOffsetY	0
	0	$\pi/2$	0	$-\pi/2$
R Elbow Yaw	0	$-\pi/2$	0	Ey
	0	$\pi/2$	0	$\pi/2$
R Elbow Roll	0	$-\pi/2$	0	Er
Torso	0	$\pi/2$	0	0

Table 3.2: DH Parameters used between right arm and torso

3.2 Body Lean

With Liu's work [24] on the new accelerometers and gyroscopes in the IMU within the Nao v4, a better estimate of the body lean became available in the robot model. Calculations so far had all assumed that the Nao's foot would be flat on the ground, however this was often not the case. Despite aiming to always keep the foot parallel to the ground, external disturbances such as bounces in the ground or pushing from other robots would disrupt kinematics. This would have particularly detrimental effects on vision and the Pose, which is used to determine the horizon and object locations on the field depending on their camera coordinates. Continuing along the chain of modules, problems in vision and the detection of key field features would affect localisation and the filtered ball location and velocity. In turn, this would ruin the precision of line ups and kicks. As such, the previous method of using purely forward kinematics to calculate the chain from the foot to the camera [28] was rewritten. Instead, the chain was separated into two sections. First, forward kinematics was used to estimate the height and location of the hip. This point would then be rotated by the forward and sideways body lean. Finally, the rest of the chain from the body to the camera was evaluated using forward kinematics once again.

Joint Frame	a	α	d	θ
	0	0	-hipOffsetZ	0
	0	$\pi/2$	hipOffsetY	0
Hip Yaw Pitch	0	$-3\pi/4$	0	Hyp
	0	$\pi/4$	0	0
	0	$\pi/2$	0	$-\pi/2$
R Hip Roll	0	$-\pi/2$	0	Hr
	0	$\pi/2$	0	$\pi/2$
	0	$-\pi/2$	0	0
R Hip Pitch	0	$-\pi/2$	0	Hp
	0	$\pi/2$	0	0
	0	0	-thighLength	0
R Knee Pitch	0	$-\pi/2$	0	Kp
	0	$\pi/2$	0	0
	0	0	-tibiaLength	0
R Ankle Pitch	0	$-\pi/2$	0	Ap
	0	$\pi/2$	0	0
	0	0	0	$-\pi/2$
R Ankle Roll	0	$-\pi/2$	0	Ar
Torso	0	$\pi/2$	0	$\pi/2$

Table 3.3: DH Parameters used between right leg and torso

3.3 Results

3.3.1 Balancing with Centre of Mass

To test its effectiveness in dynamic balancing, a simple behaviour was written to respond to any offsets in the calculated centre of mass. The motor for the Nao's left shoulder roll was made limp so that the arm could be freely moved up and down at varying angles. The change in centre of mass on the y axis would then be iteratively added to, or subtracted from, the joint value for the right shoulder roll until the centre of mass restabilised within a threshold close to 0. The left shoulder was moved at 20° intervals with the first and last being limited to the minimum value of approximately 1.7° and maximum value of approximately 75°. While compensating for the imbalance in the centre of mass, with examples as shown in Figure 3.2, the joint value for both shoulder rolls was recorded at each tick. Figure 3.3 displays a comparison of the right shoulder roll joint value at each left shoulder roll joint value over time while Figure 3.4 displays the same experiment but with opposite arms. There is a noticeable bias towards the left arm, which is discussed later in Section 3.4.

Figure 3.2 Right shoulder adjusting as left shoulder is set to 20°, 40°, 60° and 75°

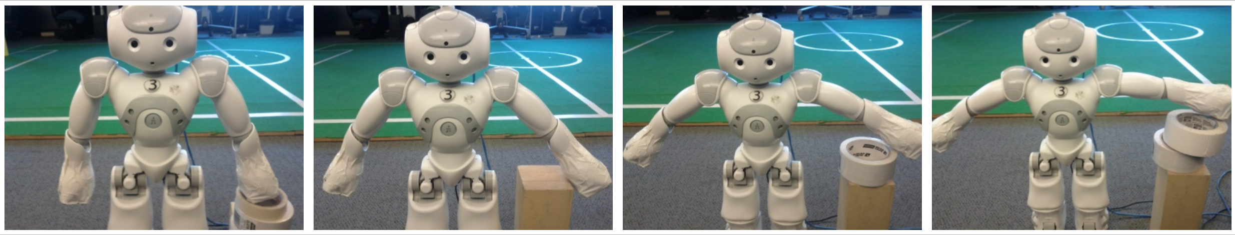


Figure 3.3 Joint values (°) as right shoulder roll adjusts to changes in left shoulder roll

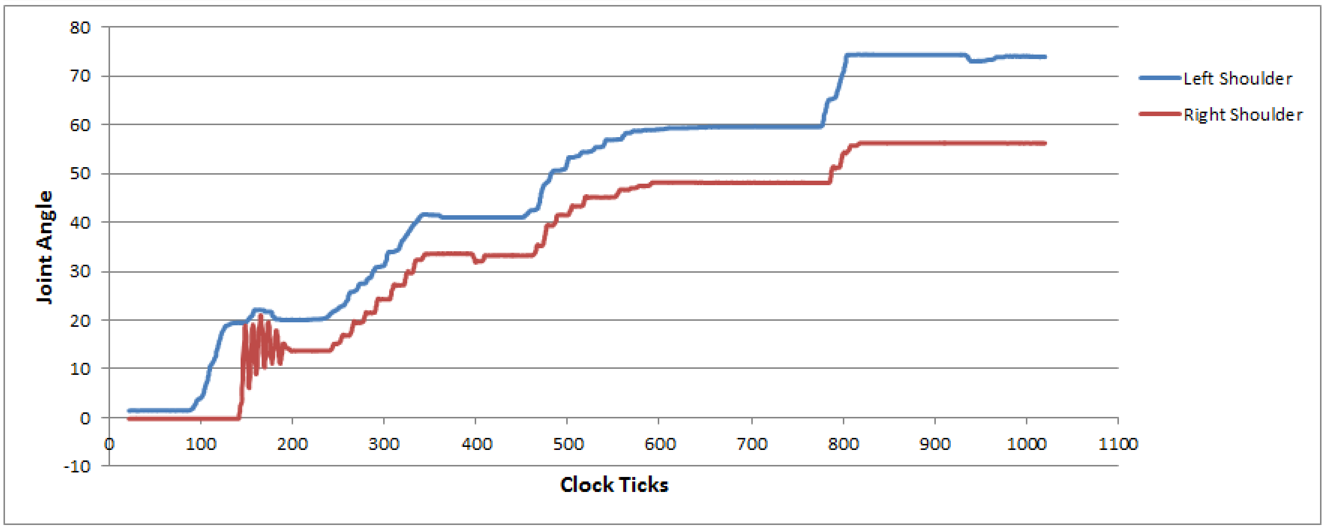
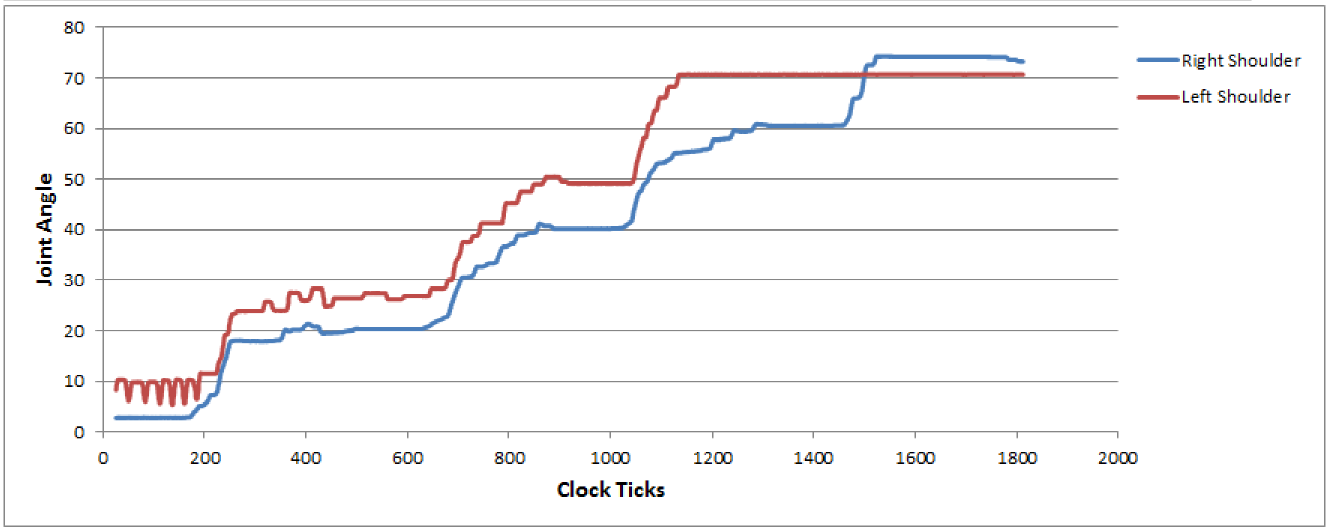


Figure 3.4 Joint values (°) as left shoulder roll adjusts to changes in right shoulder roll



3.3.2 Body Lean in Pose

The methods behind the Pose object involved the use of the Nao's kinematics chain to transform between the location of objects relative to the camera and objects relative to the ground. As such, the differences in Pose's accuracy were used as a measure of the improvements caused by the addition of the body lean in kinematics.

To test its effectiveness, a Nao was placed on the field and made to look at several key features both with and without the incorporation of body lean in its calculations. Screenshots were taken with the robot in its default stand stance and when it was tilted in both the x and y directions. For consistency, the robot was propped up by placing the same 5cm high roll of field tape beneath its foot to achieve a sideways tilt across both experiments. Similarly, a 2.5cm high roll of masking tape was used to prop the robot's feet up and achieve a forwards and backwards tilt across both experiments. Figure 3.5 shows the robot's view of the horizon when using the original method of calculating the Pose on the right, while the left displays a comparison of the same view, but with body lean incorporated. Figure 3.6 demonstrates the same concept but with projected field points and the centre circle.

3.4 Evaluation

Asymmetry in the Naos, as Tay had first suspected in 2009 [22], is confirmed once again with the results from the centre of mass. Understandably, the graphs demonstrate some lag in the adjusting shoulder as the robot received, processed and then reacted to the sensor data. This is particularly apparent in the spikes towards the start of the graphs when the arms first start to move. However, they both show a significant weighting towards the left arm being lifted higher than the right arm. The only exception to this is in the plateau at the end of the second graph, though this was due to the left shoulder roll reaching its maximum joint value. Differences in maximal joint values only serve to further the notion of the left and right joints being asymmetric, though some of the variation could be explained by the difference in stiffness and power of the motors. Aldebaran documentation does state that the right shoulder is heavier than the left by 0.17g, with the whole right side of the body weighing 1.69g more than the left. Though this would cause a slight bias, it seems doubtful that it should cause such large gaps, which are as much as 18° at its maximum angle. Other explanations could include inaccuracies in sensor readings or even perhaps that the placement of parts within the Nao's body are biased towards the right.

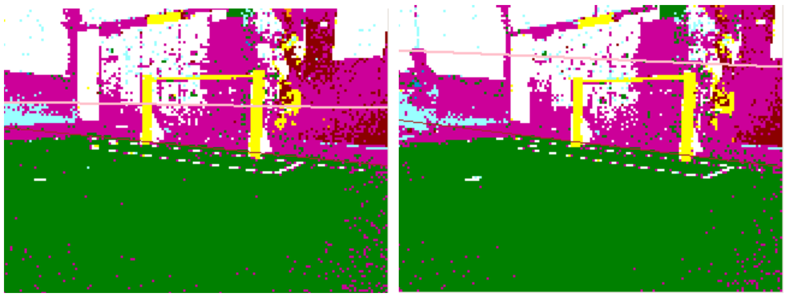
Calculating the body lean from sensor data has proven to make a significant difference, with the Nao being able to correctly detect the horizon and centre circle no matter its orientation.

Comparatively, when the Nao was tilted without incorporating the estimation of its body lean, it typically detected the horizon at incorrect angles and the centre circle at incorrect locations. In extreme cases, such as in Figure 3.6 e), the points failed to resemble a circle at all. Since the Nao was not localised, the detected circle in these images did not coincide with the white field circle, but appeared simply in the robot's relative frame of reference. It is interesting to note that without the body lean from sensor data, the horizon and centre circle were still incorrect even without a tilt in the robot's stance. This was caused by the lack of full stiffness in the motors and the default stand stance having a slight bias towards leaning forward. The Pose is still occasionally subject to inaccuracies, though this is most likely due to noise in sensor data, as well as the lack of a z-axis gyroscope in the IMU affecting the estimation of the body lean.

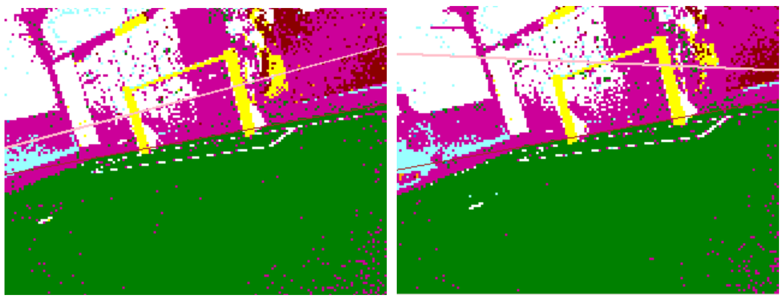
Overall the improvements in kinematics have furthered our understanding of the Nao's body model and increased its usefulness in other modules.

Figure 3.5 Comparison of horizons calculated with lean (left) versus without lean (right)

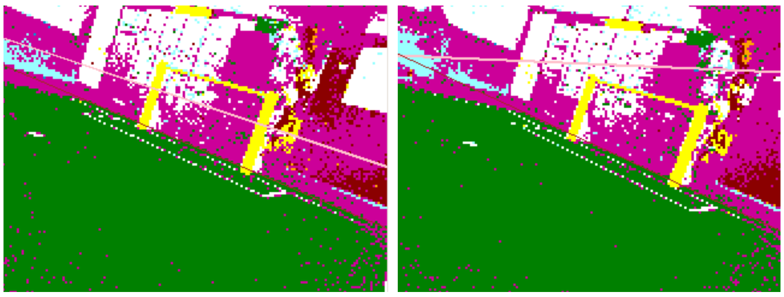
(a) No tilt



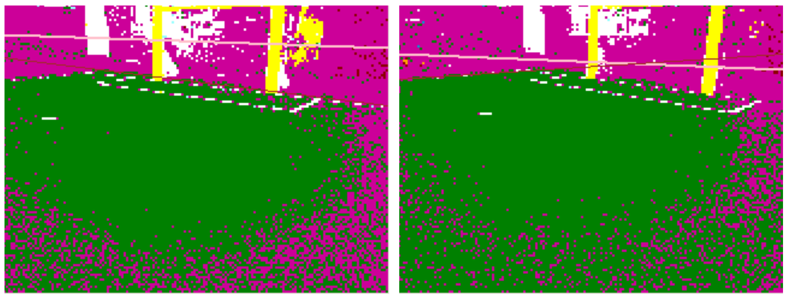
(b) Tilted left



(c) Tilted right



(d) Tilted back



(e) Tilted forward

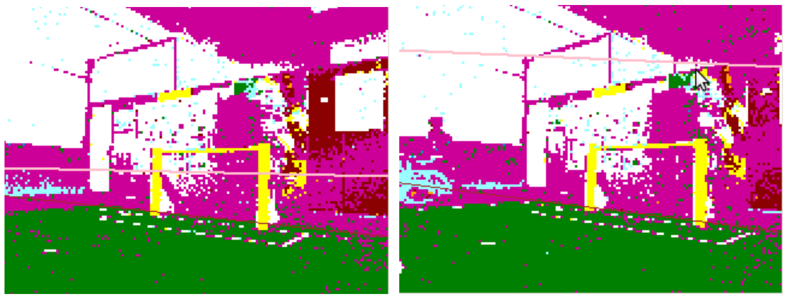
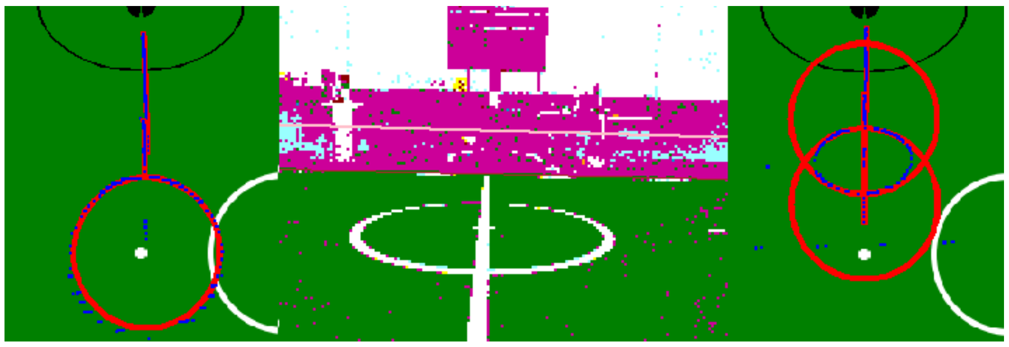
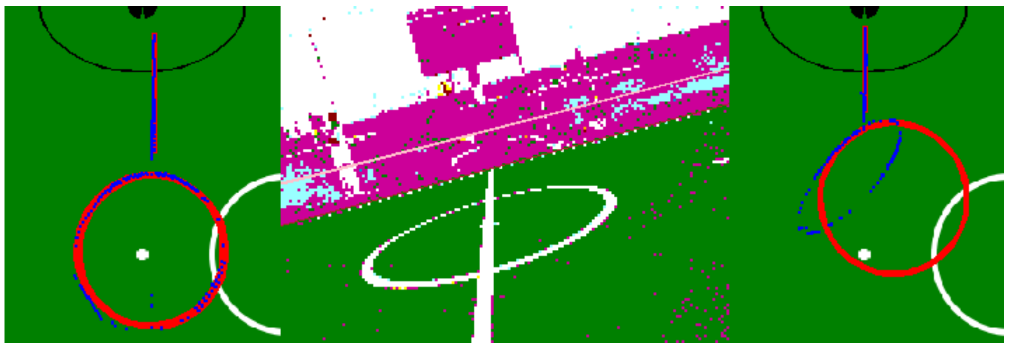


Figure 3.6 Comparison of field points (blue) and detected centre circle (red) with lean (left) versus without lean (right), with the Nao's camera view in the middle

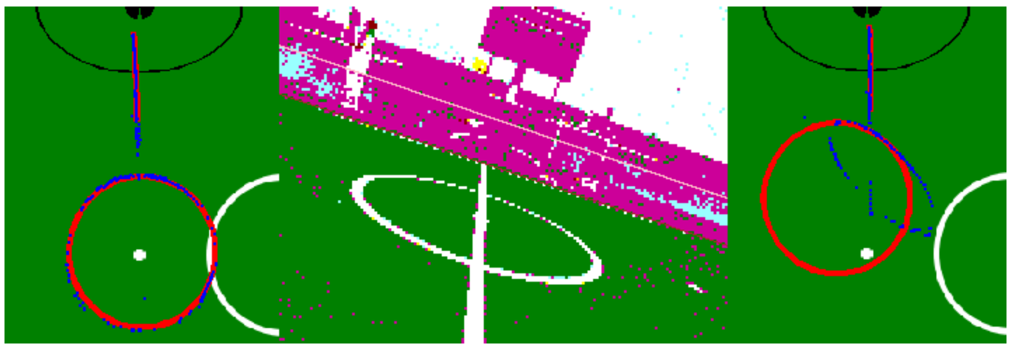
(a) No tilt



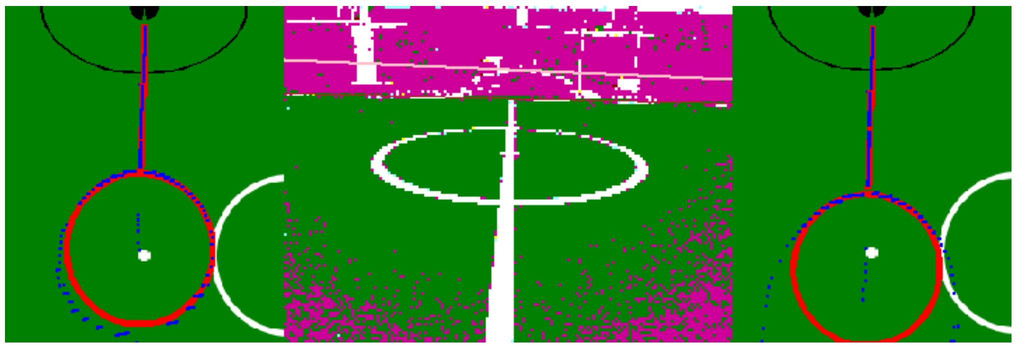
(b) Tilted left



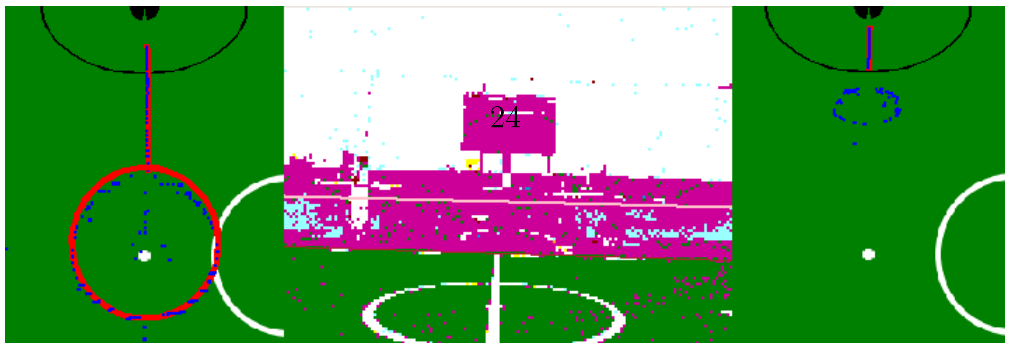
(c) Tilted right



(d) Tilted back



(e) Tilted forward



Chapter 4

Kick Engine

A kick is an action performed by moving a robot's joints in predefined manner as instructed by a state machine of timed phases (see Section 4.1.2). Since kicks are the main driving force behind moving the ball around the field and ultimately scoring goals, it is important for robots to be able to consistently kick balls with power, speed and accuracy. To achieve such movement while standing on a single foot, elements from kinematics must be used to remain balanced. Fine tuned control over the robot's body is also needed to ensure the kicking foot is in line to contact the ball with maximal power and at the appropriate angle. For the speed and flexibility of being able to kick a ball at any angle with minimal line up time, the development of an omnidirectional kick was pursued.

4.1 Background

While both forward and side kicks were available last year, these sections will mainly focus on forward kicks since the side kicks were decommissioned this year in favour of an omnidirectional kick.

4.1.1 Kick Parameters

As it was in 2011 [23], many variables were used to manage the state of the kicks within the integrated kick and walk engine:

- *currentActionType*: used within the walk engine to determine if it is currently kicking, walking, or dribbling

- *walkEngineRequest*: stores the incoming request from the walk planner at the start of the kick as the new current kick information
- *isKicking*: if the Nao is in the process of kicking
- *hasKicked*: set to true after finishing a kick
- T: period of a walk or step cycle
- t: current position within that cycle
- *footOffset*: the phase offset depending on the foot, typically either 0 or $T/2$
- *coronalAmplitude*: amplitude of the Nao's coronal rock
- *kickT*: total period of all the kick phases
- *kickt*: current position within the kick phases
- *lastKickTime*: set upon finishing a kick
- *forward/footPos*: forward position of the foot during a kick
- *left/footSide*: side position of the foot during a kick (only used in side kicks)
- *kneePitch*: how much the kicking leg is swung back and forth
- *stepHeight*: how high the foot is lifted during a kick

4.1.2 Kick Phases

As it was in 2011 [23], the phases of the forward kick were as follows:

Preparation

As soon as a kick request is received, it is saved into the *walkEngineRequest* and the preparation begins. The *currentActionType* is set to KICK, however the walk is allowed to continue until the correct support foot is on the ground. Namely, when t = *footOffset*, where *footOffset* = 0 would be the start of a left step cycle for kicking with the left foot, or *footOffset* = $T/2$ for the right foot. Once the timing conditions have been met, *isKicking* is set to true, T is set to a new slower period of 4.5 seconds, *hasKicked* is set to false and *coronalAmplitude* is set to 25°.

Weight Transfer (Start)

Using the recently set parameters from the preparation phase, weight transfer to the support foot is executed through a slow walk cycle. Note that this is caused by the combination of lengthening the period (T) and the increase in coronal rock (*coronalAmplitude*) which compensates for the slower movement. Halfway through the step, the walk cycle is paused such that the Nao is balanced on its support foot with its kicking foot lifted at *stepHeight* in the air.

Back Phase

At the start of any kick, it is assumed that the foot's position and knee pitch are at 0. The actual kick sequence then begins here, with the foot's forward position being interpolated to -70mm and the knee pitch swinging back to 20° over a period of 0.4 seconds.

Kick Swing Phase

This is the core phase of the kick, where the foot actually makes contact with the ball. The foot's forward position is interpolated to +70mm and the knee pitch is swung forward to -20°. Depending on the requested kick power, the period can vary from 0.2 seconds (maximum power) to 0.5 seconds (minimum power).

Follow Through Phase

To ensure kick phase completion and stabilisation, this phase waits at the final kick position for 1 second.

End Phase

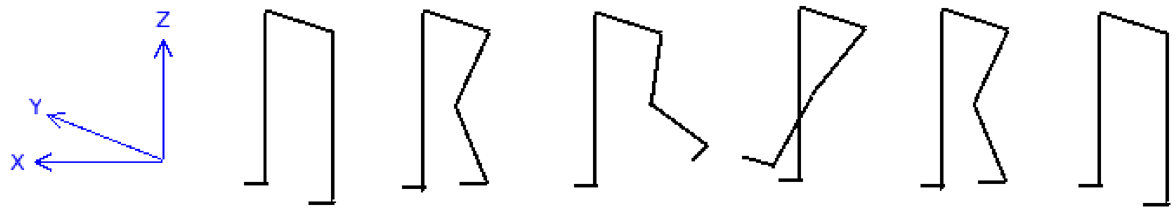
The foot is returned to its original state by interpolating the forward position and knee pitch back to 0 over 0.6 seconds. At this point the kicking foot is lifted halfway through a walk cycle with its mass balanced over its support foot.

Weight Transfer (End)

Once the End Phase has completed as checked by $kickt > kickT$, *kickt* and *lastKickTime* are set back to 0 and *isKicking* is set to false. T is still at the slow period of 4.5s, and t is updated to *footOffset* $+T/4$ to reflect the point in the walk cycle where the foot is returned to the ground and weight is shifted back into double support phase.

The movement of the legs through these phases are summarised in Figure 4.1. In total, it typically takes 4.45 seconds to execute a forward kick.

Figure 4.1 Leg movement through the main forward kick phases: preparation, start weight transfer, back phase, swing phase, end phase, end weight transfer



4.2 Angle Kick

Initial attempts to create an omnidirectional kick involved the investigation of previous years' work, namely the use of the hip yaw pitch joint to achieve an angular kick. Instead of creating a separate omnidirectional kick, the change in the hip yaw pitch joint was incorporated into the existing forward kick. However due to its exclusion from the foot position's kinematics, setting the *forward* and *left/footSide* parameters at the same time did not actually give correct results, with the ankle often tilting away from the ground. Combined with the lack of precision required in the line ups, the kick tended to be rather inaccurate. Other issues included the fact that it could only kick balls at very slight angles, otherwise the kicking leg would knock into the support leg while swinging.

4.3 Turn Kick

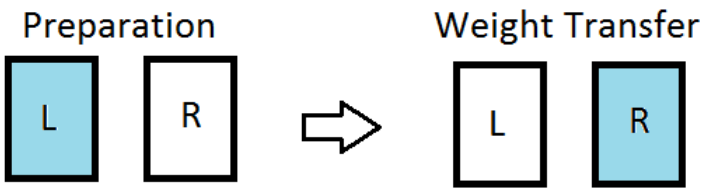
Previous approaches of turning the hip yaw pitch joint to achieve an angle kick were subject to inaccuracies, low power, complicated kinematics, and tricky line ups. Thus it was decided that it would be more ideal to reuse proven existing infrastructure, namely, the inverse kinematics used to turn whilst keeping the feet parallel to the ground when walking. Using this within the kick engine would allow enough control to turn the robot at an angle specified by behaviour, after which a normal forward kick could be carried out at full power. Hence, by first taking an omnidirectional step, an omnidirectional kick was created.

4.3.1 Taking a 'Turn Step'

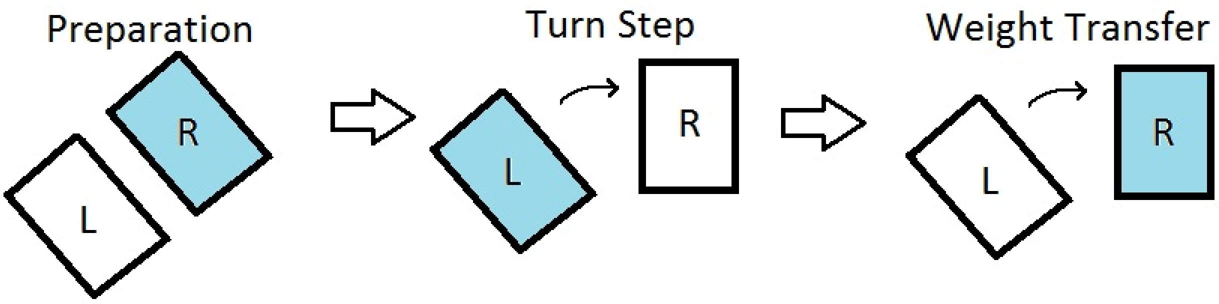
Ideally, the step should transition into the kick as smoothly and as quickly as possible. As such, it was implemented over a combination of the Preparation and Weight Transfer phases. For example, say the behaviour module requested a kick at an angle of -30°. This could be achieved by using the right foot to take a 30° turn step towards the right, followed by a straight kick. So instead of waiting for $t = 0$ to stand on its right foot and kick with the left in a typical Preparation phase, the Nao must first wait for $t = T/2$. At this point, its weight would be on its left foot, enabling it to take a step out with its right. Once the right foot lands, the Weight Transfer phase begins with the left foot turning back to straight at the same time.

Figure 4.2 Beginning phases of a left kick, with the blue background signifying the support foot

(a) Normal Forward Kick



(b) Omnidirectional Kick



To keep track of the kick state with the new turn step, additional parameters were needed in the kick engine:

- *isTurning*: if the Nao is in the process of turn stepping
- *turnAngle*: amplitude in radians of the Nao's turn step

Kick phases were thus accordingly adjusted as follows:

Preparation

This time, *footOffset* would be set to the opposite time cycle to a typical straight kick. So when turning right and kicking with the left foot, the walk would continue until *footOffset* $= t = T/2$ and vice versa. Once the timing conditions have been met, *isTurning* is set to true with *isKicking* still at false, *hasKicked* is set to false, *turnAngle* is set from the kickDirection in *walkEngineRequest* and *coronalAmplitude* is set to 13° with the period T set to 0.75 seconds.

Turn Step

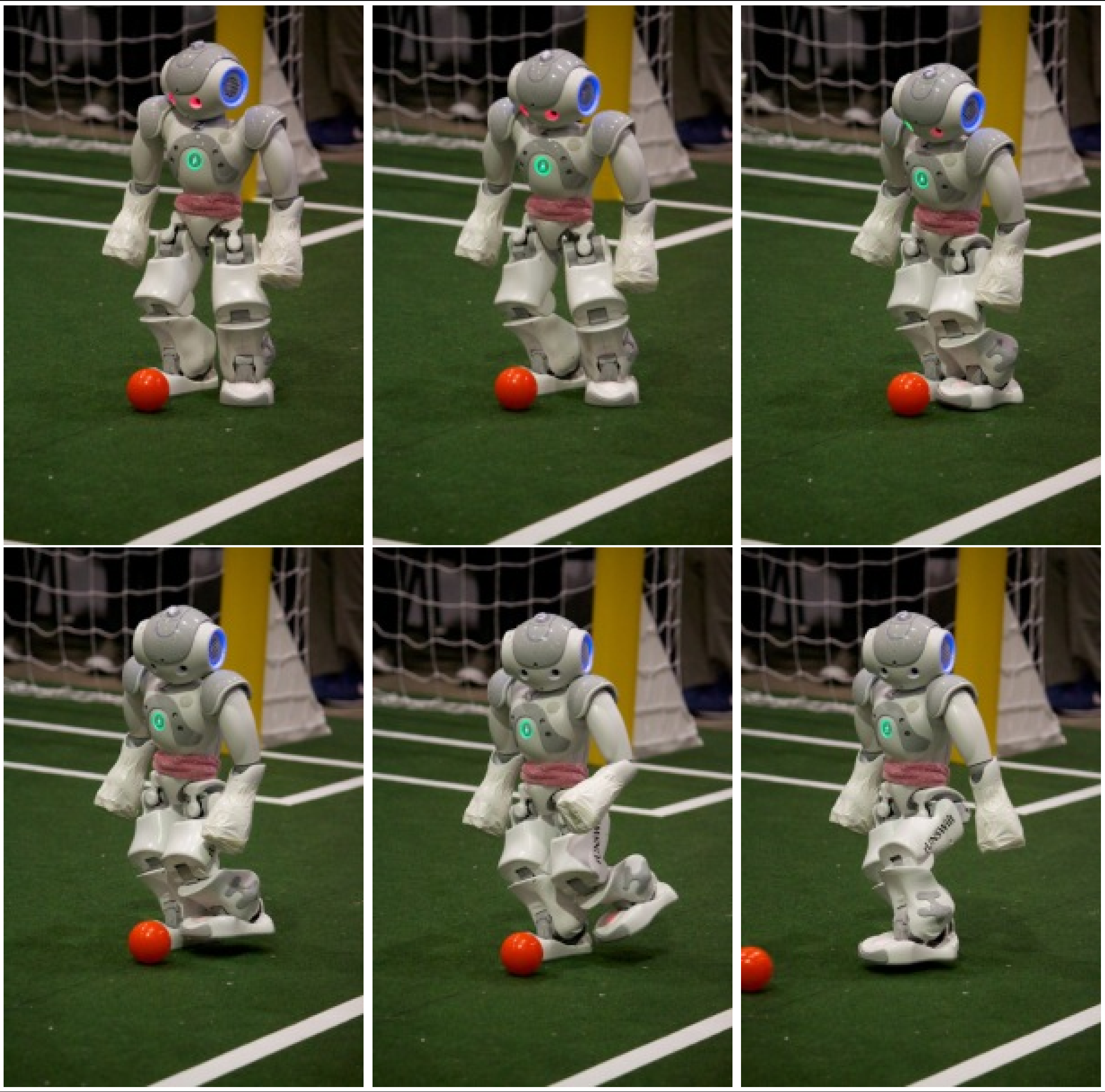
Though the step itself lasts $T/2$ seconds, the actual turn is executed within the middle 80% so that the turning foot has time to lift and does not drag against the ground. During this time, the hip yaw pitch joint is interpolated from 0 to the *turnAngle* multiplied by a *TURN_SCALE* of 1.25 to compensate for noise and lost energy. Note that the *turnAngle* is half of the actual requested kickDirection from behaviour, as both the left and right hip yaw pitch joints are connected and controlled by the one motor. Once the turn step is finished, *isKicking* is set to true and T is set to 4 seconds with *coronalAmplitude* set to to 21.45°. The kickDirection within the *walkEngineRequest* is adjusted by subtracting the turn amount so that the Nao can later continue with a normal forward kick. Finally, *footOffset* is synced back to the actual kicking foot as opposed to the turning foot. In a sense, this Turn Step Phase is an extension of the Preparation phase, as before a normal forward kick the robot would still be stepping anyway, only this time it is controlled within the kick engine.

Weight Transfer (Start)

Similar to the original Weight Transfer phase of the forward kick, the robot gradually shifts its weight onto the support foot. However, the one difference is that the swing foot is still turned outwards. Thus as the swing foot is lifted during the Weight Transfer, it is also returned to a straight orientation by interpolating the hip yaw pitch joint from *turnAngle* back to 0. Once complete, *isTurning* is set back to false. Note that the Weight Transfer phase lasts for $T/4$ seconds, however the inwards turn begins halfway through and lasts for $T/8$ seconds. This is done to ensure that the robot has sufficient time to adjust most of its weight on to its support foot, as the swing foot cannot be turned if it is still on the ground.

Figure 4.2 displays these phases and contrasts them to that of a normal forward kick using the left kick as an example. After this point, the Nao continues through the rest of the phases as part of the regular forward kick. Figure 4.3 pictures snapshots of the whole process of the kick while it is performed on an actual robot.

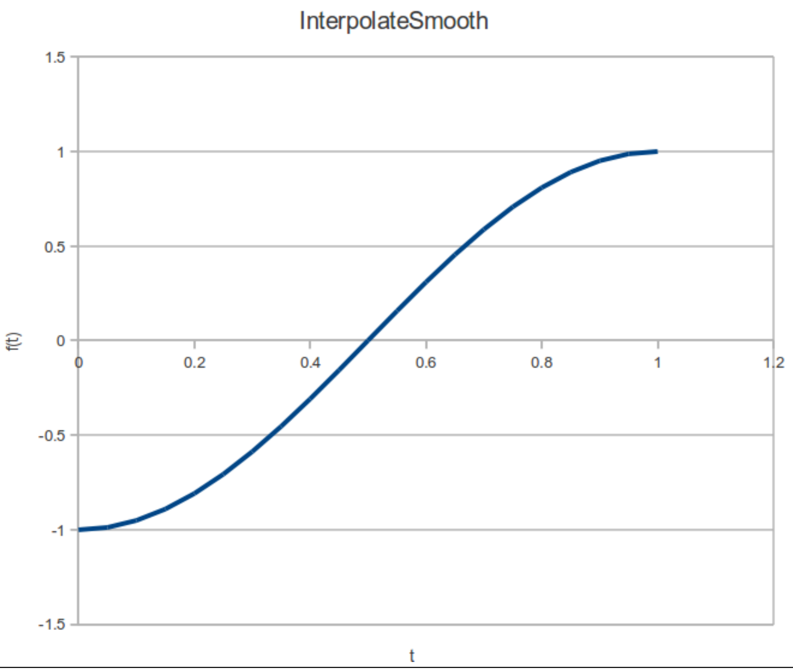
Figure 4.3 Snapshots of the dynamic omnidirectional kick in motion



4.3.2 Kick Adjustments

Further improvements were made to the kick for speed and reliability. Regarding speed in particular, the method in which the joints moved from phase to phase could be enhanced. This is currently conducted using a function known as interpolateSmooth, which takes a section of the sine function and stretches it out to the desired length over a given time period [23].

Figure 4.4 An example of the interpolate function from -1 to 1 [23]



Firstly, since this interpolate function is based on a sine wave, the point of maximum speed and momentum would occur at the middle of the curve. Secondly, the further away the point of interpolation, the faster the interpolation must occur in order to remain within the same period. Thus to speed up the kick, the knee swing was set to interpolate from 30° to -40°. Shifting the centre of the sine curve just past $x = 0$ would cause the foot to contact the ball, which would be located just in front of the foot, at maximum speed. However, to ensure that the leg remained within inverse kinematics and joint limits, the knee pitch was capped at a forward maximum of -10°.

Now since the knee swing was set separately, unlike the foot's forward or left position which made use of kinematics, the foot would not always remain parallel to the ground. This could cause problems if the robot was leaning slightly, as parts of the foot could scrape against the ground. Another occurrence would be if the ball was slightly too far forward, as during the leg's forward swing, the ankle would tilt up, potentially causing the robot to step on the ball instead of kicking it. All of these would typically cause the robot to fail to kick, fall over, and in particular cause wear to the knee and ankle joints if scraped against the ground. Thus, to balance out the change in knee pitch, new parameters were added:

- *anklePitch*: how much to tilt the ankle pitch to compensate for the swinging knee pitch and keep the foot parallel to the ground
- *ankleCompliancePercent*: scaling factor to tune the degree of adjustment in the ankle pitch

During the Kick Phase, ankle pitch was interpolated from -5° to 30° but capped at a forward maximum of 5°, half of the knee pitch. The added benefit of levelling the ankle was that the kick gained an increased forward reach as it would be able to actually kick the ball, as opposed to step and slip on it, further improving the kick's reliability.

The period of many of the phases were also adjusted to be shorter. Perhaps it was due to the more powerful motors of the Nao v4s, but numerous trials found that the kicks could be sped up without losing balance and reliability. Improving the time taken to transition into actually kicking was particularly important, as it meant we would be able to keep control of the ball and move it in optimal directions before opponent robots could get in the way. Table 4.1 displays the changes in phase times for each of the kicks assuming they are at maximum power. Note that these values represent the actual time spent in the phase as opposed to the period of the cycle (T). The times of 0.25 seconds for the Preparation phases of the normal forward kicks are taken from a typical step period in the walk engine.

Phase	2011 Forward Kick	2012 Forward Kick	2012 Omnidirectional Kick
Preparation/Turn Step	0.25	0.25	0.375
Weight Transfer (Start)	1.125	0.5	1
Back Phase	0.4	0.4	0.4
Kick Phase	0.2	0.2	0.2
Follow Through Phase	1	0.4	0.4
End Phase	0.6	0.5	0.5
Weight Transfer (End)	1.125	0.875	0.875
Total	4.7	3.125	3.75

Table 4.1: Break down of time (s) between all the kick phases

4.3.3 Dynamic Adjustments

One of the main motivations for the omnidirectional kick was to improve the striker's line ups by removing the need to spend time lining up the foot exactly with the ball position in the desired kick direction. As such, dynamic adjustments were needed to improve the reliability and execution of the kick. A common problem amongst lining up involved taking multiple steps until the middle of the foot lined up with the ball, however this would become subject to the speed and precision of the walk cycle. Thus it was decided that dynamically adapting the foot out to the ball position would be implemented within the kick engine instead. This would prove useful for reducing the number of steps taken before kicking a ball and increasing the kick's sideways reach, which would be particularly beneficial for the omnidirectional turn kicks as they require stricter line ups. In order to incorporate this new information, the MotionAdapter class was modified to read in the ball's filtered position from the Localisation section of the Blackboard. It would then be passed down through the DistributedGenerator until it reached the WalkEngine. To keep track of how much the foot should actually move, a new parameter was created:

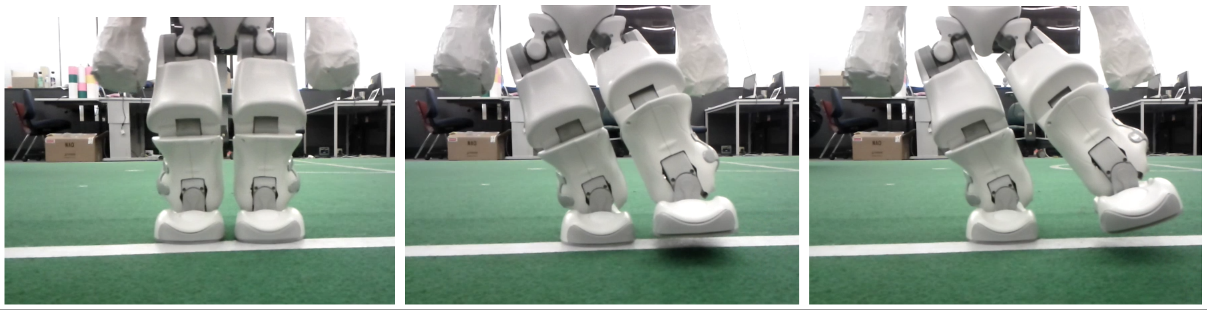
- *omniSide*: how much the foot should be moved in the y direction as based on the ball's y position, fed into *left/footSide* parameter

The sideways adjustment was applied throughout the start of the kick and up to 90% of the Back Phase. Since the foot needed to be straight by the time it came into contact with the ball for minimal loss of accuracy, this was was the latest time in which the dynamic movement could be added.

One issue with rUNSWift's current method of inverse kinematics is that the positions are defined relative to the hip's frame of reference as opposed to the ground's. When the foot is moved out to the side, the hip roll increases to the opposite side to balance out the robot's change in centre of mass. However, due to the nature of the hip roll joint, the kicking leg is rolled slightly upwards as well, causing the foot to be higher relative to the ground (see Figure 4.5). As such, additional parameters separate to inverse kinematics were needed to ensure the kick's success:

- *shoulderRollAmplitude*: how much to lift the arm over the kicking foot so it does not get in the way
- *anklePitchAmplitude*: how much lower the ankle should be tilted to compensate for the hip lift and still make contact with the ball, (added on top of the *anklePitch* parameter)
- *left/hipLean*: how much more the hip should shift over the support foot to stay balanced in compensation for the additional changes

Figure 4.5 The upwards roll in the hip as a robot goes from standing, to leaning during a kick, then to reaching its leg out further for a ball on the side



Other external disturbances during games include being pushed by other robots in the middle of a kick, which can happen very often in close tussle situations. This became another opportunity to make use of the newly available body lean to dynamically adjust the tilt of the kick. Depending on the forward angle and sideways angle of the body lean, the Nao could modify the ankle pitch and ankle roll joints respectively. These values would then be compounded with the ankle adjustments as mentioned in the previous section. Similar formulae already existed in the walk engine's balance adjustment, and were simplified down into the negation of a scaled and filtered version of the body lean. They would then be applied to the tilt of the ankle pitch and roll if *isKicking* was set to true. Thus by dynamically adjusting the ankle pitch and roll and ensuring the foot stayed parallel to the ground, the chances of a successful kick no matter the surrounding circumstances were increased.

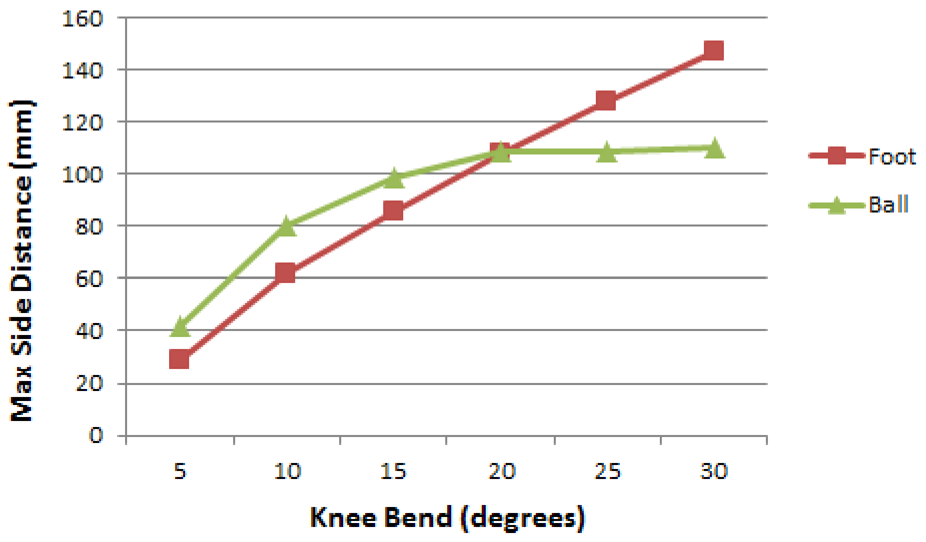
4.4 Results

4.4.1 Omniside Reach

With the addition of the *omniSide* parameter, the robot's foot could be adjusted sideways to kick balls without having to line up directly behind them. However, due to the limit of each of the joints and kinematics calculations, the foot's dynamic side position could only go so far. As such, a reasonable maximum had to be determined to limit the foot's movement and decide how accurately the robot should line up to kick the ball. This maximal distance would also measure how effective this improvement would be at saving line up time.

The side reach was dependent on the support leg's knee bend as the lower the hip, the further the foot could reach out while still making contact with the ball. An experiment was set up to measure how far the foot and the ball could move outwards with the Nao still managing to kick the ball straight according to varying knee bends. 5 kicks were performed at each 5° increase in leg bend, starting at 5° to allow the leg at least some movement to begin with. The maximum sideways foot distance as specified in the walk engine and the average measured maximum sideways ball distance are compared in Figure 4.6. Note the sideways foot distance is specified as an offset within the walk engine through the *left/footSide* parameter, with the maximum found by testing the limits of the joints and kinematics. Sideways ball distance is measured as the difference between the location of the centre of the ball if it were placed for an ideal straight line up, to the location of the centre of a ball at the limits of the kick's reach. Unlike the foot, the ball's maximal side distance follows a non-linear trend, which is at first more and then less than the foot's maximal side distance. This is discussed further in the Evaluation in Section 4.5.

Figure 4.6 Reachable foot and ball side distances according to varying leg bends



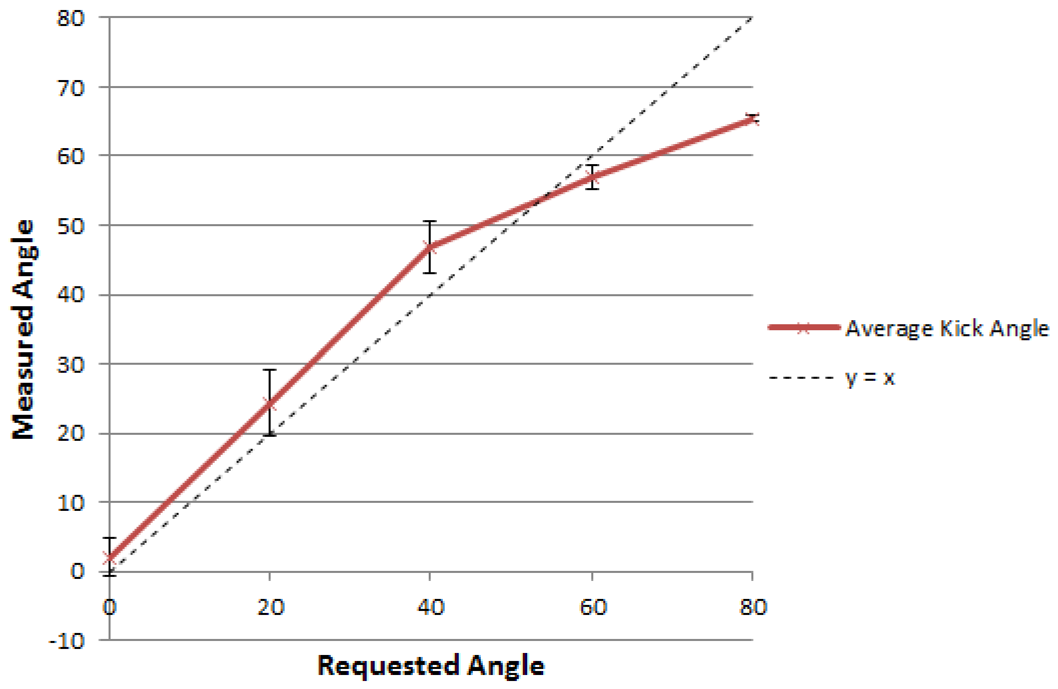
4.4.2 Omnidirectional Accuracy

To test the accuracy of the omnidirectional kick, 5 left kicks were performed at increasing intervals of 20°. The robot was placed just within the centre circle facing the goals with the ball placed in the middle of the field. It was then told to kick out towards the centre circle at a certain angle, similar to a kick off situation. Since the surface of rUNSWift's SPL field was not always even, the point at which the ball crossed the centre circle line was marked down, as this was before the ball could begin to drift sideways down the field. Accuracy was then measured by comparing the angle in which the ball had travelled to the angle requested by behaviour. Table 4.2 displays the recorded angles in degrees with Figure 4.7 illustrating the average trend and the error in standard deviation.

	Measured Angle (°)				
Requested Angle (°)	1	2	3	4	5
0	-0.79	0.19	5.44	4.65	0.99
20	21.80	27.96	23.17	30.24	18.28
40	41.72	43.95	49.73	50.51	48.41
60	58.37	55.43	55.17	56.92	58.81
80	65.07	-	65.52	65.74	-

Table 4.2: Recorded angles through increasing degrees of the omnidirectional kick

Figure 4.7 Average measured kick angles and their standard deviation compared to requested kick angles



4.4.3 Kick Power

To test the improvements in the forward kicks and their effects on the kick power, an experiment similar to White's in 2011 [23] was set up. Note that the power results also apply to the omnidirectional kick as it reuses the forward kick as its base. Five balls were kicked from the centre of the goal box and allowed to roll to a stop. The distance from the centre of the ball at its starting location to the centre of the ball at its final location were then measured. Both the kicks at their half power of 0.5 and full power of 1.0 were compared. The resulting ranges of the kicks are summarised in Table 4.3. There is a noticeable lack of power in the right kick compared to the left kick, and this asymmetry is discussed in Section 4.5.

	2011 Range (m)		2012 Range (m)	
	0.5	1.0	0.5	1.0
Left Kick	2.20-2.71	5.10-6.50	4.42-5.09	5.75-6.97
Right Kick	2.54-2.89	2.54-2.91	2.95-3.35	3.04-3.89

Table 4.3: Comparison of the range of kick distances from 2011 and 2012 at varying powers

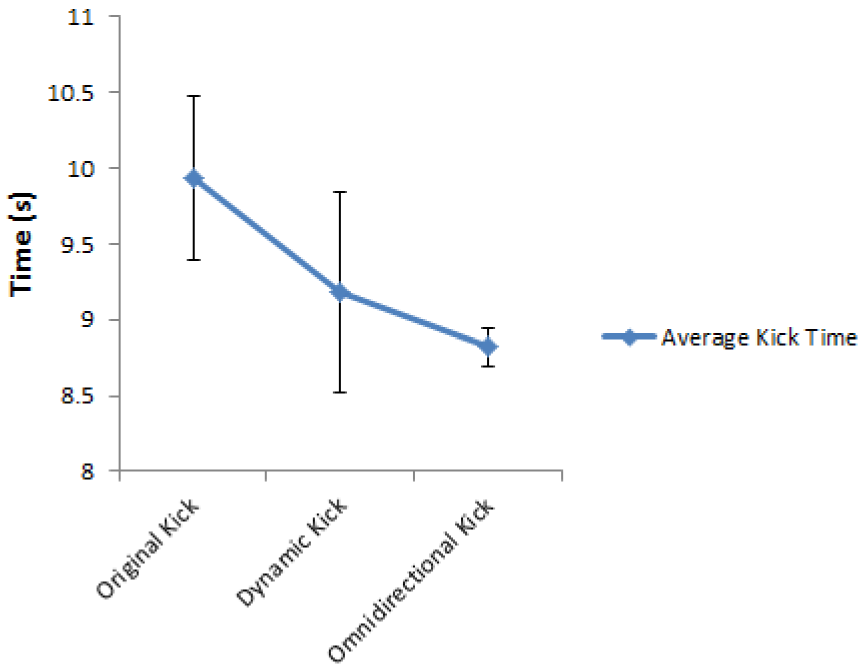
4.4.4 Simple Striker Test

Finally, to test the speed of the new omnidirectional kick in game situations, a simple Striker test was constructed. The Nao was placed at the middle and side of the field facing the centre circle with the coordinates (0, -2000) and a heading of -90°. The ball was then placed right in the centre of the field. Time was measured from the point when the Nao entered the centre circle to when the ball crossed the goal line. 5 trials each were performed for the original forward kick, the kick with dynamic side reach, and finally the complete dynamic omnidirectional kick with turn step included. Table 4.4 displays the recorded times, with Figure 4.8 comparing the average time and standard deviation for each kick.

	Original Forward Kick	Dynamic Forward Kick	Dynamic Omnidirectional Kick
Trial 1	9.5s	9.4s	9.0s
Trial 2	10.0s	8.8s	8.7s
Trial 3	9.3s	9.2s	8.8s
Trial 4	10.6s	10.2s	8.9s
Trial 5	10.3s	8.5s	8.7s

Table 4.4: Recorded times from the centre circle across the progress in kicks

Figure 4.8 Comparison of average kick times and their standard deviation across the different improvements in kicks



4.5 Evaluation

With rUNSWift's current method of kinematics for leg positions, the ankle joint, and hence the foot, was able to move a reasonable distance outwards from its typical straight kicking position. Since the foot is approximately 80mm wide, with the flattest area at the front being approximately 45mm wide, it was still able to connect with balls that were slightly further away than the position of the actual ankle joint. As the start of the graph in Figure 4.6 shows, the ball can be placed up to 20mm further to the side of the specified foot position and still be kicked. However, the ball's side distance eventually plateaus at a maximum of around 110mm. As mentioned earlier in Section 4.3.3 , due to the nature of the frame of reference in which kinematics is calculated, the further the foot is placed outwards, the more hip lean required. But instead of simply moving to one side, the hip joint began to roll upwards, causing the foot to rotate upwards as well. This ankle roll can actually be observed in the last frame of Figure 4.5. By the end of the graph, the ankle roll joint had reached its maximum, meaning the foot was no longer parallel to the ground and no longer had its wide contact area. At this point, only the very tip of the inside edge of the foot could still make contact with the ball. Thus the maximum knee bend worth pursuing to attain the robot's side reach of 110mm was at 20°.

Although other methods of moving the knees and feet might provide better side reach results, the reason for this approach and the decision for the eventual leg bend took into account multiple factors. Mainly, many of these methods and parameters overlap with those used in the walk. The knee bend in particular is a crucial parameter, with a requirement that both legs have the same bend for a symmetrical and stable walk. There is also a trade off in that a lower bend results in a faster walk but applies increasing amounts of stress on the robot's knees. The knee bend for kicks and walks should not differ significantly, as large changes in knee bend, especially while rocking, can throw the robot off balance. Additionally, if the knee is already quite bent, there is less swing available when performing the kick, causing it to lose potential power. Finally, even if a low leg bend was chosen for a further side reach, the greater the shift in the foot's side position, the less stable and unreliable the kick became. As such the final chosen leg bend ranged from 16-25°, which reflected the range in speeds in which the walk could perform at. Since the walk would slow down just before kicking, the actual leg bend used in kicks were typically around the lower range towards 16°.

The dynamic addition of side reach would prove particularly useful as a contributing factor to the success of the turn step and omnidirectional kick. The larger the turn angle, the further to the side the ball would be after the turn. Hence without the omniside component, it was possible for the omnidirectional turn kick to connect using the side of the foot instead, or in the worst case, it would miss all together. As section 4.4.2 of the results show, the final omnidirectional kick actually had quite a reasonable success rate with fair accuracy up until 65°. The slight but consistent bias towards the right up until around 40° suggests that the dynamic side offset in the foot is tuned too far outwards. This would cause the ball to connect on the inside of the left foot and travel more towards the right. However, the bias towards the left on the 60° kick suggests other factors are involved. It is likely that the *TURN_SCALE* used to exact the turn step should not be a simple constant, but adjusted less for smaller angles and more for larger angles. Once past about 65° though, the omnidirectional kick becomes ineffective. As shown in the results from the 5 trials for the 80° kick, 2 of them are nonexistent due to the kick's instability and failure to complete. It seemed that 80° was too wide a turn for the Nao to complete within a single step as well as the period and coronal rock constraints. Out of the 3 kicks that successfully completed, all were subject to the same instabilities that caused their turn step to land earlier than anticipated. While this did prevent the robot from falling over like the 2 failed trials, it also meant that the turn was cut short, hence the resulting degree of 65°.

The next measure of the new kick's success was how powerful it could be. All the kick adjustments proved their worth, with the 2012 left kick surpassing the 2011 left kick by 0.47-0.65m and being able to consistently kick a ball almost the length of a field, if not past it. If it were not for the uneven surfaces in the field and the loss of energy in rolling sideways down the field, the minimum kick range would be even higher. Also, since rUNSWift's SPL field ended at approximately 6.5 metres, the last sections involved the ball losing energy by rolling off the edge of the field and on to bouncier carpet. Hence, the actual maximum kick range also had the potential to be even higher. While the 2012 right kick did surpass the 2011 right kick by 0.5-0.98m, it was still significantly weaker than the left kick. Although the exact reasons are unknown, it is suspected that the mass differences and asymmetry in the Nao would play a part. In fact, without the dynamic body lean adjustments, the right kick was unable to perform at a full power of 1.0 as the foot would keep kicking into the ground. This suggests that there might also be issues with asymmetry in the left and right side motors, which seem to either produce more noise or are unable to keep up with the speed of the left.

Overall the new dynamic omnidirectional kick has been a success and quite an improvement over last year's methods. As Figure 4.8 shows, adding the dynamic adjustments such as the side reach improved scoring time by just under a second on average. Combining the turn step on top of that reduced the average time by around a further half a second. It was particularly effective with the robot's approach from the side of the field as the method in which we walk and turn around the ball to face the right direction allowed for smooth transitions into the turn step. Although the total time of the dynamic omnidirectional kick was not always faster, it was more consistent, with all 5 trials reliably scoring goals within 9 seconds. This kind of reliability is essential as it contributes to ensuring victory in actual matches, even during high pressure situations. However, it is important to note that the line up and times are heavily influenced by the other modules in the rUNSWift code. For example, fluctuations in vision quality and localisation accuracy can contribute to the speed of the line up and precision in kicking the ball.

Chapter 5

Dribble Kick Engine

Governed by the *currentActionType* being DRIBBLE, the dribble engine sits as a subset within the kick engine, which itself is a subset of the walk engine, with similar parameters and phases. Similar to a regular kick, a dribble kick is another predefined movement aimed at keeping the ball moving around the field. Its main purpose is to supplement the robot's movements with a kick focused on speed and manoeuvrability at the cost of power and accuracy. This is particularly important in situations where opponent robots are nearby and contesting the possession of the ball. Speed is of the essence, as the first robot to nudge the ball away will typically gain the advantage. Once again, focus will be applied to the forward dribbles as opposed to the side dribbles.

5.1 Background

5.1.1 Dribble Parameters

As it was in 2011 [23], many of the parameters used by the dribble engine were shared amongst the kick engine. However, a few additional variables were used to help keep track of the dribble state:

- *hasDribbled*: set to true after finishing a dribble
- *lastDribbleTime*: set upon finishing a dribble

5.1.2 Dribble Phases

Similarly in 2011 [23], the dribble kick phases were as follows:

Preparation

In a similar fashion to a kick request, once a dribble request is received it is saved into the *walkEngineRequest*. Once the correct support foot has landed, *currentActionType* is set to DRIBBLE, *hasDribbled* is set to false and the period T is set to 1.4 seconds with *coronalAmplitude* set to 20°.

Kick Phase

The Kick Phase encompasses what would be a typical Weight Transfer (Start) Phase, as the kick motion simply occurs through a slightly longer period of the walk cycle. During this phase, the foot is interpolated forward to 70mm over 0.7 seconds.

End Phase

The foot is return to its original state by interpolating backwards to 0mm over 0.7 seconds. As soon as the phase is complete, *hasDribbled* is set to true. This then triggers what would typically encompass a typical Weight Transfer (End) Phase, as the parameters are set back for normal walking. In particular, this involved setting *lastDribbleTime* to 0, returning *currentActionType*, T and *coronalAmplitude* to their normal walk values and updating t to reflect the current foot cycle.

5.2 Forward Dribble Kicks

5.2.1 Kick Adjustments

Like the forward kicks, it was found that many of the phases and parameters could be tuned for increased speed and power. More specifically, the period T was decreased to 1.2 seconds, with the *coronalAmplitude* adjusted to 13.5 accordingly. The foot's interpolated forward position was also increased from 70mm to 95mm during this time. For an even faster impact, a similar approach from the forward kick was applied to shift the peak of the interpolation sine wave forward towards the point of contact with the ball. This was done by interpolating the foot's forward position 25mm past the desired position, then capping the final value to retain stability.

5.2.2 Dynamic Adjustments

To improve the line up speed for dribbles, the *omniSide* parameter was used as a dynamic adjustment once again. Like the forward kicks, it allowed the foot to adjust sideways depending on the ball location. However, since the forward dribble period was much shorter, there was not nearly as much time to adjust the foot. In fact, the side reach was only adjusted during the first 20% of the dribble in order to contact the ball at a straight and consistent angle. The leg bend was also typically less than it would be during normal kicks due to the dribbles being able to occur mid-walk. As such, the side reach was not particularly far, but considering that accuracy was not as paramount in dribbles, it was still faster than no dynamic adjustments at all.

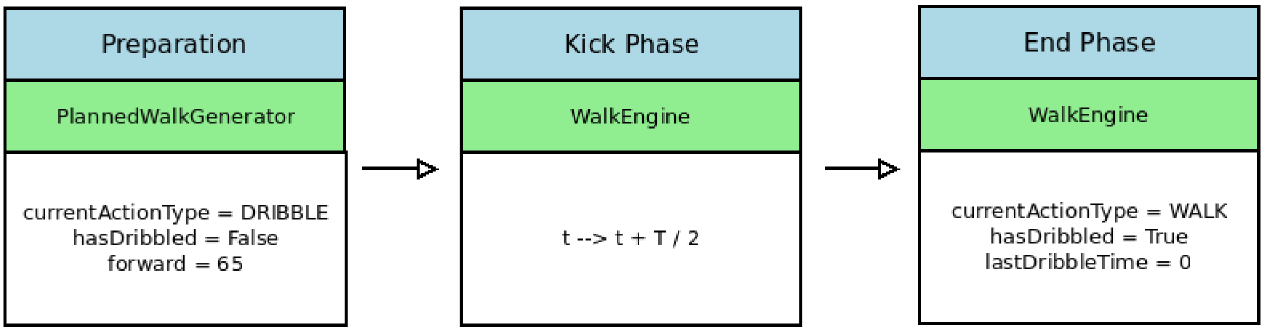
5.2.3 Walk and Dribble Integration - the Forward Shuffle

While the current dribbles are faster than the kicks when it comes to nudging the ball away from opponents, they are still nothing like a human's. Ideally, the robot should be able to move with the ball and continue chasing after it. Rather than interpolating the foot back to a position of 0mm, it should use its momentum and stride to keep taking a step. A sideways shuffle was attempted by White in 2011 [23], which involved sidestepping with one foot in front of the other. However, it was unstable and was never perfected for competition. Instead, a new approach of using both the PlannedWalkGenerator and the WalkEngine to better integrate walking and dribbling was devised in 2012. A new forward shuffle was thus created to follow a ball forward, both dribbling and stepping at the same time.

While simply walking into the ball would be ideal, inaccuracies could result from contacting the ball with different edges of the foot. Depending on which part of the step cycle the robot was in, it could also produce unreliable power. As such, the robot was made to roughly line up to the ball first from within behaviour. The shuffle dribble was then called upon using the *isFast* parameter, which was originally only used for turning on the Fast Walk in the walk engine. Eventually this information was passed down through to the PlannedWalkGenerator, which is where the walk's steps are actually controlled and planned out.

Forward and backward movement during the walk is typically applied when the robot is in between steps, so this timing was reused for the forward shuffle. At this point, the PlannedWalkGenerator would set the relevant parameters in its child WalkEngine. Namely, *currentActionType* would be set to DRIBBLE and *hasDribbled* would be set to false like a normal dribble. However, instead of manipulating the joints or feet position directly, the walk parameters *forwardL* and *forwardR* within the walk request were set to 65mm.

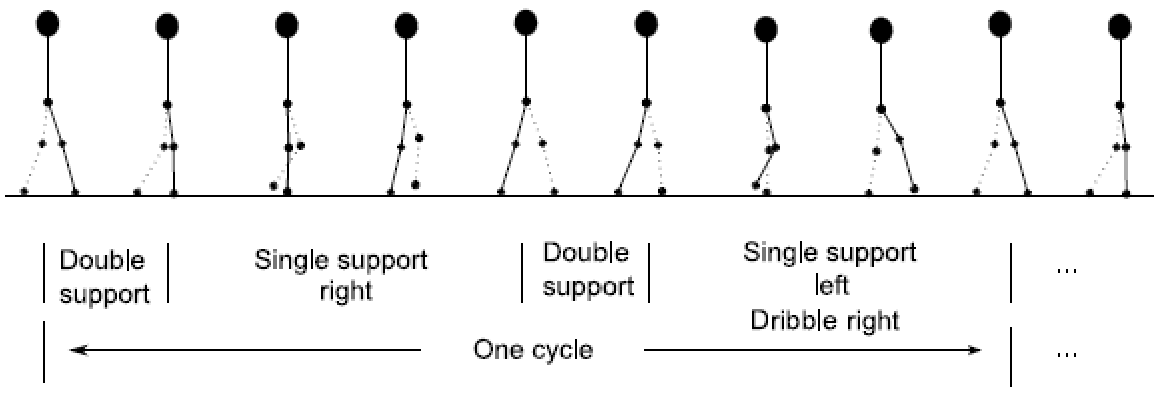
Figure 5.1 Changes in key parameters during a shuffle, with blue representing the current dribble kick phase and green representing the controlling class



Control would then fall to WalkEngine, where although the *currentActionType* was set to DRIBBLE, the *isFast* parameter was used to make sure all the walk cycle functions were still applied. Based on the requested foot, it would ensure that the correct phase and subsequent *footOffset* was in place. Meanwhile, the previously set walk parameters would automatically ensure that the foot would take the appropriate forward step during this phase. Once a time of $T/2$ had passed and the phase was complete, the robot would continue walking as normal with the relevant dribble engine parameters returned to their previous state. *currentActionType* was returned to WALK, *hasDribbled* to false, with *lastDribbleTime* being reset to 0. The flow of these states are pictured in Figure 5.1.

Unlike the other dribbles and kicks, there was no need to change the period or coronal rock as the shuffle would smoothly continue as part of the walk. The walk cycle and its support phases are shown once again in Figure 5.2, with slight modifications to the leg movements to display the integration of the shuffle. As an example, dribbling the ball with the right foot occurs during the exact same time as a normal left support phase in the walk, with the swinging right foot being extended more forward than usual.

Figure 5.2 An example of the shuffle's timing within the walk cycle



5.3 Results

Unlike the forward kicks, the ideal qualities in a dribble are not accuracy or power, but speed and versatility. However, these can vary greatly depending on the occasion and the strength of the opposing team. As such, the results described in this section are based on the tussles that occurred during actual competition matches from Robocup 2012. In the early matches, rUNSWift's dribbles managed to win all close tussles and keep the ball moving away from nearby opponent robots. This was particularly showcased when rUNSWift stole the ball away with a forward shuffle in a defensive kick off at 5:06 in the match against the Dutch Nao Team, and dodged through all 3 of TJArk's robots with 2 forward shuffles in a defensive kick off at 10:44. Another successful case was the goal against the Austrian Kangaroos at 6:52, where a forward shuffle was used to quickly knock the ball in right next to the goalie. However against stronger teams with fast dribbles of their own, the outcome was not always favourable. Close tussles against teams such as B-Human and Austin Villa involved at least 2 dribbles before the ball would pop out towards the side, with both robots chasing the ball only to ensue yet another tussle. Although rUNSWift's dribbles were still sometimes effective, such as at 13:14 against HTWK in the third place play-offs, their goal was scored by surging past all four of rUNSWift's robots with their strategy of constantly dribbling.

It was however found that the forward shuffle as opposed to the forward dribble was not ideal for the goalie. There was an occasion were the goalie performed the forward shuffle to avoid an incoming opponent, and then continued dribbling onwards past the other robots. Instead of stepping forward to chase the ball, the goalie should simply clear it and be able to return to a defensive position if need be. As such, the behaviours were modified using the *isGoalie* flag to separate the use of the forward dribble in the goalie and the forward shuffle in the striker.

5.4 Evaluation

The dribbles were a useful addition to the rUNSWift arsenal, with ball possession being retained throughout most of the early matches, even during defensive kick offs. Many of rUNSWift's high scoring matches of 10 - 0 and multiple fast goals of less than 20 seconds would not have been possible without their speed and manoeuvrability. They were also on a competitive level with the more advanced teams, as evidenced by the close games against B-Human and Austin Villa. The forward shuffle proved useful not just for nudging the ball away, but for continuing after it in order to retain possession of the ball.

However, the most effective direction in which to dodge an opponent is not necessarily always forward. The lack of a side shuffle meant that rUNSWift's robots did not have as much sideways agility. Even if the forward shuffle managed to nudge the ball past an opponent, the striker robot itself would need to pass the opponent to continue kicking the ball and avoid being caught for pushing. A sideways shuffle, on the other hand, would be much more effective for allowing the striker to dodge past as well. Unfortunately, development on such a manoeuvre was begun but not polished in time for competition.

Chapter 6

Pos Actions

While the more complicated motions of walking and kicking had their own engine, other actions, such as standing and getting up for example, were simply governed by a series of joint angles. If behaviour requested one of these actions, the DistributedGenerator would send the request down to the ActionGenerator, which would then refer to the file for the relevant action. The basic structure of such a file, known as a .pos file, was created in 2010 [16] and would contain entries, each consisting of the angles for each joint in degrees. This would then be followed by the duration of that particular movement in milliseconds and the end of the line. In 2011 [23], this was expanded upon to include an additional optional line for controlling the motor stiffness in each of the joints.

6.1 Front Getup Routine

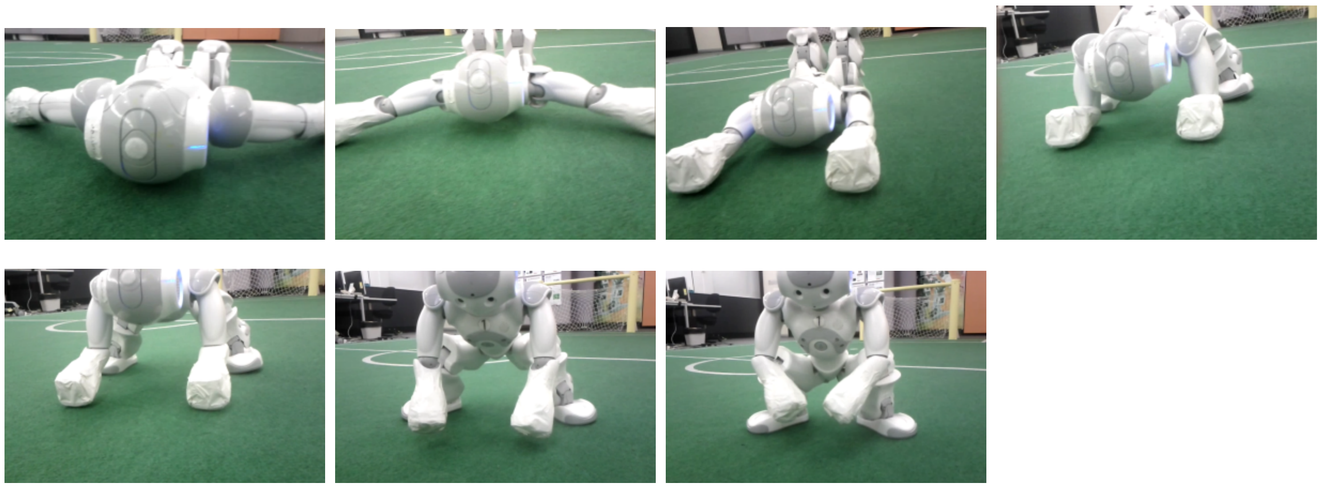
Being able to get up is a very important skill for a soccer robot, especially since instabilities in bipedal motion mean they are highly susceptible to falling over. A fallen robot would be unable to kick the ball and could even obstruct team members from getting to the ball due to the amount of space required to perform the getup routine. Removal penalties would also be applied if the robot continuously proved unable to get up or pushed other robots in the process of attempting the getup [29]. Since getup routines are defined as set actions in .pos files, care must be taken to program the joints with the appropriate momentum to shift the robot's centre of mass off the ground and back to a standing stance.

This chapter focuses on the improvements made within the front getup routines in particular. For work on other actions such as the back getup, refer to Liu [24].

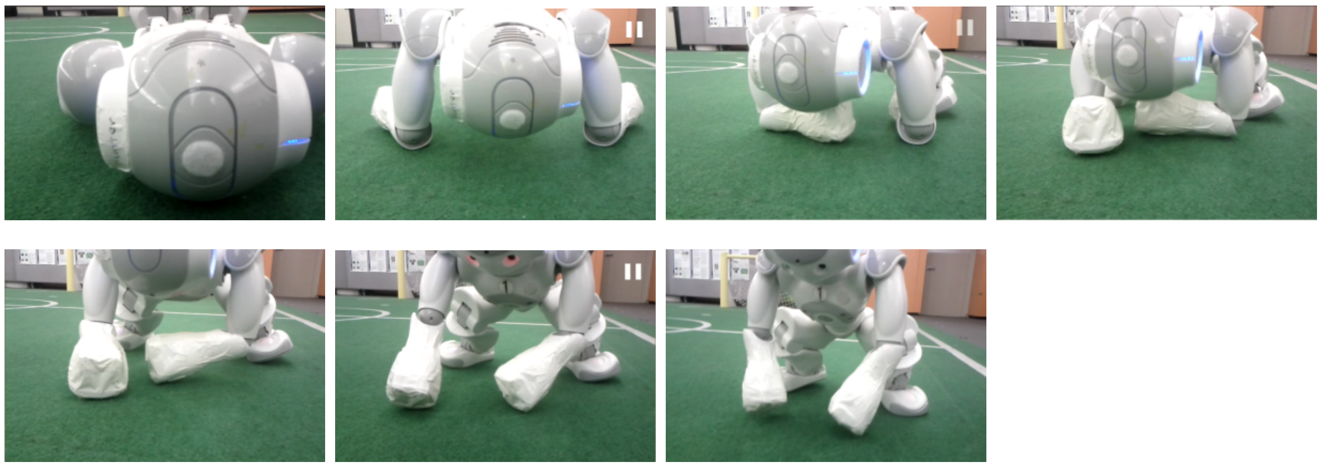
6.1.1 Arm Swing

Figure 6.1 Snapshots of the movement of the outward versus inward arm swings

(a) Original outward arm swing



(c) Modified inward arm swing



The main drive behind the front getup routine is the sliding of the arms in towards the body for backwards momentum and extending them off the ground to give the upper body more lift. Since the state in which a robot falls is unknown, the first step of the getup routine is to realign the body straight on the ground with its arms by its side. Next is to swing the arms around and up above the head to begin the sliding motion. Now the problem with this is that by the nature of the shoulder joints, the arms must be fully extended in order to be swung upwards from the side of the body. This ends up taking up a lot of space, with the potential for the arms to knock against some object and interrupt the getup routine, thus causing the robot to fail at getting up. In the worst case, the robot's swinging arms could push over robots nearby, resulting in a pushing penalty. By manipulating the arm joints to swing the arms inwards and underneath the torso, these space issues would be drastically reduced. As such, the robot would instead be able to get up more reliably in much more confined spaces. This would prove critical in close tussles with multiple robots, especially since such situations would often cause at least one robot to fall. A comparison of the original and modified arm swing movements are displayed in Figure 6.1.

6.2 Results

The final arm swing method was tuned till the robot could get up for 10 times in a row. Once finalised, it was compared to the original by measuring the differences in arm lengths and the area used. It was found that moving an arm inwards as opposed to having it outstretched to the side took up 23cm less space. Thus, the new arm swing brought the total saved space beside the robot to 46cm. Since the arms were no longer extended above the robot's head either, this saved another 12cm in the forwards direction. Along with a smoother combination of some of the latter standing steps, the whole getup routine had also decreased from 5480 to 4500 milliseconds.

Table 6.1 describes the number of attempts at a getup before the robot successfully stood up. The column 'Removed' counts the getups that were never given a chance to complete due to being penalised and removed from the field. These results are tallied according to each of rUNSWift's matches in Mexico City during Robocup 2012.

	Number of Attempts			
Match	1	2	3	Removed
1 - Robocanes	1	0	0	0
2 - Dutch Nao team	1	0	0	0
3 - B-Human	0	1	0	0
4 - Austrian Kangaroos	3	2	0	1
5 - TJArk	1	0	0	3
6 - UPennalizers	6	2	0	0
7 - Austin Villa	0	0	1	0
8 - Nao-Team HTWK	0	1	0	0
Total	12	6	1	4

Table 6.1: Attempts per forward getup across rUNSWift's games during Robocup 2012

6.3 Evaluation

Considering the ideal qualities of a getup routine are speed and reliability, the new front getup performed very well in testing. In game situations, the decrease in area taken up by the outwards arm swing was crucial in enabling the robots to get up in confined areas. As Table 6.1 has shown, the majority of the front getups ended in success. In fact, an added benefit was found when a robot fell on top of the ball in Game 6 against UPennalizers. While getting up, the new arm swing managed to sweep the ball out from under the robot and avoid the ball holding penalty. The increase in the amount of getups towards the middle of the competition reflect the increase in competition, with more robots on the field being aggressive around the ball and poor networking causing failures in team communication. The increase in attempts required as well as subsequent failures can also be attributed to robots getting worn out from continuous matches. Many of the repeat attempts and one of the removals were due to incomplete shoulder motor actuation. In total, the 4 removals were caused by the robots being penalised twice for fallen robot, once for pushing, and once for ball holding. The following decrease in front getups were due to the walk being slowed down in an attempt to reduce the risk of pushing and falling down, as well as a significant improvement in wireless networking and team communication.

However, much work remains to be done as robots were still subject to falling over mid-getup. One of the main issues of the front getup was its heavy reliance on the Nao's arms. The more the robot was made to perform the getup, the more the shoulder motors became worn out. In fact, many of the failed getups were a result of one of the robot's having an erratic shoulder pitch motor. A possible solution would be to move away from applying such stress on the arms and to instead make more use of the legs and swinging momentum to get up. Another problem was the static nature of the getup routine, as the joints are moved through a set series of positions as opposed to a dynamic generator. While the use of a .pos file is a simple and clear solution, it does not allow for any adjustments to external disturbances such as pushing or resistance from nearby obstacles. Additionally, every robot differs slightly in their manufacturing, so perfectly tuning a .pos file for one robot could become moot on another.

Chapter 7

Striker Behaviour

The culmination of all the improvements would ultimately be tested in rUNSWift's striker, which was defined as the robot set to attack the ball and was typically the closest as well. This behaviour was an opportune chance to apply the new kicks and speedier line up techniques. The main purpose of the striker behaviour was to score goals, or at least kick the ball away from opponents, as quickly and reliably as possible. However, since the goalie could sometimes become the robot in charge of attacking the ball, the lower level behaviour of kicking a ball was abstracted into a state machine in the class known as *Shoot*. Final actions were then controlled or overrided by the higher level decision tree in the *Striker* class.

7.1 Low Level State Machine - Shoot

The main aim of this behaviour was to kick the ball into the goal, and the following points list the *Shoot* specific states required to carry out such a task:

- **GoToBall**: uses WalkToPoint [30] to aim for a point just behind the ball in the x direction, with a slight bias to the right in order to line up with the left foot
- **WalkAroundBall**: if approaching the ball from the opposite goal direction, turn and step around the ball while still facing it until kicking into the opponent's goal is possible
- **LineUp**: once the robot is close enough to the ball, it lines up in front of the ball with its foot in position for a straight kick then sets up parameters for KickBall
- **LineUpSlightAngle**: a subclass of LineUp but for omnidirectional kicks with a relatively small angle

- **LineUpWideAngle**: a subclass of LineUp but for omnidirectional kicks with a relatively wide angle
- **LineUpDribble**: lines up the robot in front of the ball for either forward or side dribbles and shuffles
- **KickBall**: performs the actual kick or dribble according to the given parameters and ensures the kick completion before continuing to chase the ball

Tasks common to other behaviours were also used by simply calling upon externally written skills. These non-striker specific states are summarised as follows:

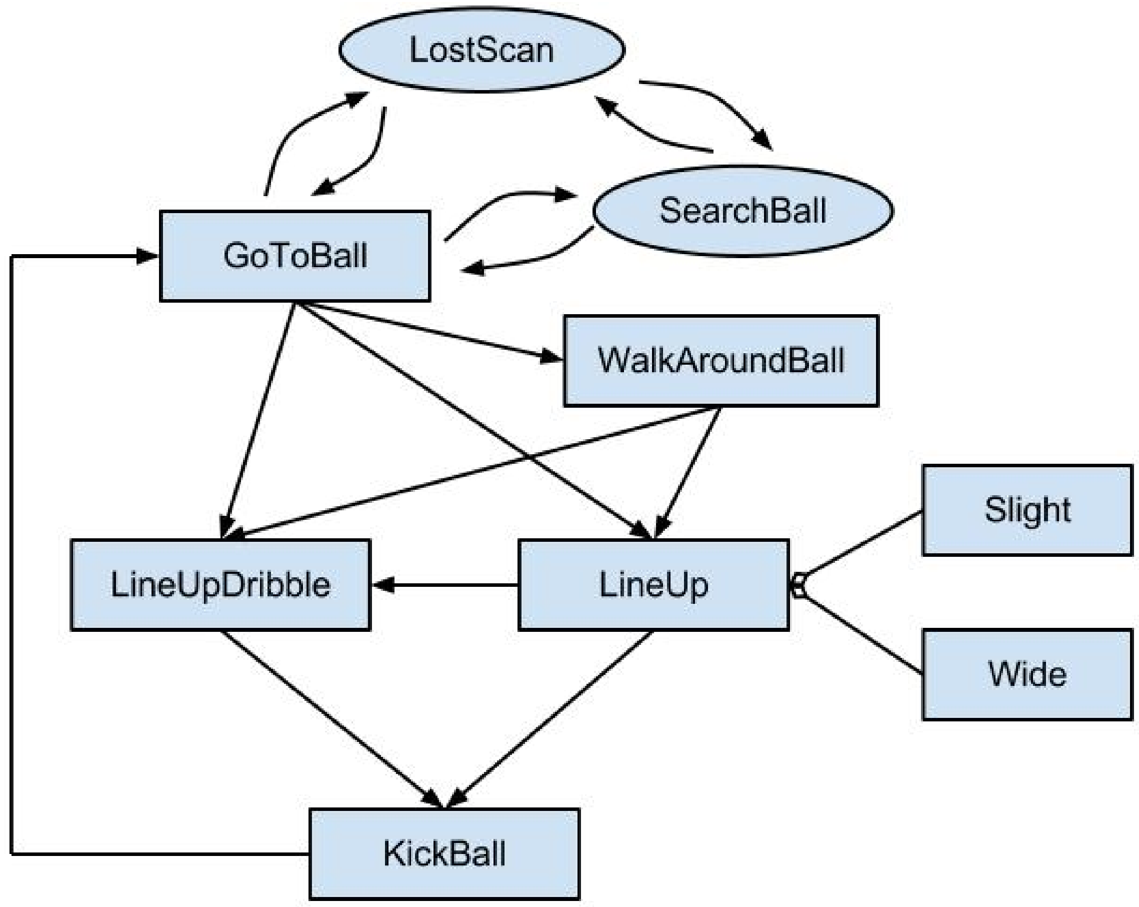
- **LostScan**: stands still and performs a wide scan, only used if the robot is totally lost [31] which typically occurs after returning from a penalty
- **SearchBall**: pans the head in search of the ball, occasionally turning the body if need be [30]

There are also many parameters used to keep track of the robot's actions, including:

- *isRelative*: boolean set by higher level behaviours (such as *Striker*) for interrupting normal kick flow with higher priority dribbles
- *targetDir/angleDir*: the angle from the robot to the goal direction at the ball
- *kickAim*: used to aim kicks either around a goalie, or in an absolute direction during kick offs
- *useLeft*: whether or not the left foot should be used to perform the kick
- *strict*: whether or not the robot should line up more strictly during dribbles as opposed to just kicking in a relative direction
- *absDir*: the angle at which the robot should strictly line up to
- *kickDir*: the robot relative direction of the kick for use in the walk engine
- *kickFoot*: sets the foot type of LEFT or RIGHT
- *kickType*: sets the action type of KICK or DRIBBLE
- *power*: strength, ranging from 0.0 to 1.0, at which the robot should kick at

The general flow of *Shoot*'s states are shown in Figure 7.1, with rectangles representing *Shoot* specific states and ellipses representing states of external origin. GoToBall is the main entry point of the states, however it must first establish its location as well as that of the ball before it can proceed with its main task. Once close enough to the ball, the robot proceeds into either one of the LineUpDribble or LineUp states and its children. Control can also pass to LineUpDribble even if the robot is amidst one of the LineUp states as long as the high priority parameter *isRelative* is set. Finally, after kicking the ball, the cycle continues with the robot returning to the GoToBall state.

Figure 7.1 Key flow between states in the Shoot behaviour



7.1.1 Penalty Shoot-out States

In the case of a tie, it was possible for the match outcome to be determined by a penalty shoot-out [29]. Since the main aim was to kick the ball into the goal yet again, *Shoot* was used as the underlying class. rUNSWift's strategy was to first dribble the ball closer to the goals, pause to localise and ascertain the goalie's location, then kick the ball as normal. However, extra parameters and an extra state were needed to supplement the penalty shoot-out's specific behaviour.

Parameters:

- *isPenalty*: boolean responsible for determining if the robot was in a penalty state, and for starting the chain of penalty states if need be
- *donePenaltyDribble*: boolean to keep track of whether or not the initial dribble towards the goal had already been carried out

States:

- **PenaltyLocalise**: since the normal striker never actually localises, this penalty state is needed to stand the robot still and uses HeadSkill to perform a conservative left to right scan over the goal area.

7.2 High Level Decision Tree - Striker

Generally, behaviour was left to the *Shoot* class to carry out, as most of the time the striker would simply try to score goals. However, there were a few striker specific cases that needed to be handled.

7.2.1 Kick Off Strategy

Originally the kick off play was to dribble and pass the ball to a supporter robot on the side. However, dribbles were not particularly reliable when it came to distance or accuracy, so time would be wasted catching up to the ball. If the pass missed significantly, opponent robots would have a chance to reach the ball at the same time or if not before us. Either way, it was incredibly likely that a close tussle could occur near the middle of the field. This was highly dangerous as the tussle outcome might not always be favourable. A kick could be used instead to aim for slightly ahead of the supporter robot with more reliable power and accuracy. Ideally, the supporter would just have to move forward and wait just behind the designated area to receive the pass. However, this was slower as it had to turn more to line up, and was still potentially dangerous as it was still fairly close to the middle of the field. In particular, if the kick fell slightly too far backwards and behind supporter, the whole play would have backfired instead. It was also important to consider the starting position of the kick off, as the robot would be more likely to achieve a location with advantageous vantage points during the *Ready* skill. For example, if the robot was turned too far to the side, it would not be able to see the opposite goal posts, but if it was simply facing forward, it would not be able to see much of the halfway line.

Thus the final strategy was to kick the ball forward and slightly to the left, aiming for the corner of the opponent's goal box. Ideally, the ball would roll between the positions of the opponent's striker and supporter robots, meaning the opponents would have to waste time turning around to get back around the ball. The supporter would continue to move forward to be in an advantageous position to kick the ball in from the side. Meanwhile the original striker would move forward to chase the ball, either switching to a central supporter position, or continuing in to contest the ball if need be. Even if rUNSWift's robots did not arrive there first, the ball, and hence the subsequent tussle, would be much closer to opponent's goal box. This was a much safer strategy as even if tussle was lost, the ball would not have travelled far and could be gained back. The kick off angle was roughly 20°, which was incorporated into the *Ready* skill to reduce line up time. Conveniently, this ready location was beneficial for seeing both the halfway line and goal posts in the same frame and staying localised. Now since the striker had to clear the ball from the centre circle yet not score a goal, the right kick was used to ensure a lower and more controlled power.

7.2.2 Robot Avoidance

While general robot avoidance around the field was handled by the *WalkToPoint* skill, the striker also needed to adjust its kick strategy if there were robots nearby. In close tussle situations, it was important to keep the ball moving forward rather than waste time lining up, especially if it would disrupt an opponent's line up. With improved robot detection [32], it was possible to detect if the robot nearby was friendly. Normal kicks could still be carried out unless the friendly robot was directly in front, in which case dribbles would be more beneficial. Typically, the striker would try and dribble the ball towards the enemy goal, or at least away from the enemy robot. However, if the striker could not decide on an appropriate dribble approach, control would be left to the *Shoot* skill. It would line up around the ball and aim with a big kick, which still had a chance of bypassing opponents or at least only rebounding slightly. The following algorithms (1 - 3) describe the process for deciding which kick and direction would be most suitable.

Algorithm 1 Striker's decision process for avoiding enemies once detected

```
myAngleToGoal ← normalise(ballAngleToGoal - robotPos.theta)
kickDirs ← [left, right, forward]                    ▷ Set up the 3 possible directions
for kickDir in kickDirs do
    if not possible(myAngleToGoal, kickDir) then
        remove kickDir
    end if
end for

if $LEN$(kickDirs) $> 0$ then                  ▷ Pick the best out of the possible directions
    bestDir ← findBestKickDir(kickDirs, myAngleToGoal)
    if bestDir == forward then
        use forward shuffle
    else
        use relevant side dribble
    end if
else                              ▷ Check if forward direction is towards the goal anyway
    kickDirs ← [left, right, forward]
    bestDir ← findBestKickDir(kickDirs, myAngleToGoal)
    if bestDir == forward then
        use forward shuffle
    else
        let Shoot line up and kick
    end if
end if
```

Algorithm 2 Function for deciding which direction is most suitably towards the goal

```
function findBestKickDir(kickDirs, goalAngle)
    bestDir ← kickDirs[0]
    minDiff ← $180°$
    for kickDir in kickDirs do
        curDiff ← $ABS$(kickDir - goalAngle)
        if curDiff $<$ minDiff then
            minDiff ← curDiff
            bestDir ← kickDir
        end if
    end for
end function
```

A similar approach to robot avoidance kicks was made for the goalie, just with more conservative thresholds and defence mechanisms. In particular, it would always line up at an angle that would block the goal and dribble the ball forward, in other words, outwards from the goal.

Algorithm 3 Function for deciding if a kick direction was possible

```
function POSSIBLE(goalAngle, kickDir)
    if $ABS$(goalAngle - kickDir) $> 70°$ then        ▷ If goal angle difference is too high
        return false
    else if close to own goal and $ABS$(goalAngle - kickDir) $> 20°$ then
        return false
    else if the ball will roll out then
        return false
    else if an opponent robot is near in that direction then
        return false
    else if any robot is too close in that direction then
        return false
    end if
    return true
end function
```

7.2.3 Close Range Goals

If the striker was close to the goals, instead of using a big powerful kick, it would be more desirable to quickly close the gap with a dribble and score. Even if an enemy robot was nearby, the dribble would typically be fast enough to score anyway. If there was a goalie right in front, then at worse the ball would bounce off towards the side. Typically this would be close enough to the goal that the rebound would enter the goals anyway, if not it would still be close enough to the goals for another dribble. Speed was of the essence, as if the goalie had a chance to clear the goal area of the ball, the opportunity would be wasted and the striker robot would be setback behind the ball.

7.2.4 Illegal Defender Penalty

Finally, at the highest priority was the avoidance of the illegal defender penalty [29]. Since the striker behaviour would typically chase after a ball, a special case was put in place for when the ball was in its own goal box. No matter what the situation, the robot would stop moving further forward once close to the goals, only turning to keep facing the ball with the occasional localise head scan to ensure that it was actually at its own goal box. Although this was no elaborate strategy, it was simple and efficient at avoiding the detrimental 30 second penalty. By staying localised and staring at the ball, it would contribute useful information to the team ball, hopefully aiding the goalie in getting to the ball instead. Additionally, the striker robot would typically be in a convenient location both to block opponent robots from going straight to the ball and to follow up the goalie once it cleared the ball.

7.3 Results

7.3.1 Striker Test

As an ongoing measure and motivation through out the time leading up to the competition, weekly tests of the striker were performed. These involved timing how long it took for a robot to localise from a certain position, get to the ball, and score a goal. The ball would be placed in the centre of the field with the robot at a specified position and orientation. Table 7.1 summarises the best times in mm:ss.SSS from across this year according to each starting position of x, y, heading, and compares them to the best times of 2010 and 2011, of which only mm:ss times were available.

Start Position	Best Time 2010	Best Time 2011	Best Time 2012
a) -1200, 0, 0	00:13	00:16	00:11.04
b) -1200, 2000, $-\pi/2$	00:34	00:31	00:19.00
c) -1200, 0, $-\pi$	00:40	00:26	00:13.50

Table 7.1: Comparison of striker test times over rUNSWift's past three years

7.3.2 Robocup Competition 2012

The ultimate measure of the striker's performance was at the international Robocup competition itself in Mexico City. Kick offs were generally successful, with 18 out of 19 managing to get the ball past the penalty spot and near the goal box if not intercepted by an opponent robot. The 1 out of 19 ended up hitting a robot slightly in front of the penalty spot, and can be attributed to the striker's manual placement in the ready skill, causing it to lose its distance advantage. In some cases, the ball managed to roll into the goal box but just short of scoring a goal. Such an example occurred three minutes into rUNSWift's match against Austin Villa. The kick off triggered a dive from Austin's goalie, and rUNSWift's supporter robot managed to come from the side to score a goal in a total time of 20 seconds from Ready to the ball passing the goal line. Robot avoidance was also generally effective, as can be seen from the dribble results. The illegal defender strategy prevented rUNSWift's robots from ever incurring such penalties, of which there were six ample opportunities. Progress was sometimes slow however, as there was an occasion where there were not enough robots contributing to the team ball, so the goalie was unable to find and clear the ball. This was still much more than other teams, for example, 11 illegal defender penalties were called for HTWK during the third place play-offs compared to 0 for rUNSWift. Although, during that same game, rUNSWift did cause a local game stuck to be called for two robots before a global game stuck was finally decreed. However, this was ultimately more beneficial anyway, as play would restart at a kick off as opposed to the ball being in the goals with multiple robots penalised.

In terms of actual score, rUNSWift performed remarkably well with a total of 62 goals scored during matches. This was by far the highest scoring team, with B-Human and Austin Villa numbering second and third with 55 and 54 goals respectively (excluding penalty goals). rUNSWift also performed its fastest this year with some of the speediest goals during the competition. Of note include the 12-13 second goals in the games against the Dutch Nao Team and Robocanes. Overall, rUNSWift placed third at the competition of Robocup 2012.

Match	Goals Scored	Goals Conceded
1 - Robocanes	10	0
2 - Dutch Nao team	10	0
3 - B-Human	3	4
4 - Austrian Kangaroos	8	1
5 - TJArk	6	0
6 - UPennalizers	8	0
7 - Austin Villa	6	7
8 - Nao-Team HTWK	11	1
Total	62	13

Table 7.2: Final scores from each of rUNSWift's games at Robocup 2012

7.4 Evaluation

The striker has improved compared to the previous years, with new record times set for each of the striker test positions as shown in Table 7.1. During the Robocup competition, the sheer number of goals scored showcases the striker's ability, with the final result being a very close third place by one goal. There were however multitudes of factors that contributed to the striker's improvement and success.

On a behavioural level, the fresh rewrite removed many of the layers that only served to clutter and slow down the striker. In particular, the multi-layered line up code that existed in the previous skill classes of Shoot, Aim and Kick were unnecessarily repetitive. As previously mentioned in the results from the Kick Engine, the creation of a dynamic omnidirectional kick improved the times measured from simple striker tests, which would have contributed to the success of the striker behaviour during competition. More steady kinematics would in turn improve line up accuracy, further reducing the indecisive stepping at the ball which was so common in previous strikers. Another important time reduction was the lack of a CheckLineUp state, which the old strikers used to double check their localisation and aim just before taking a shot. Along with the removal of the Localise state, these improvements would not have been possible without major advancements in localisation and landmark detection [31,32]. Finally, the new robot detection system incorporating both vision elements and the sonar filter [32] allowed for more strategic aiming for goals and quick reactions when dribbling down the field. Overall, the striker's focus on simply getting to the ball and kicking it as quickly and accurately as possible proved a great asset to the rUNSWift 2012 team.

Chapter 8

Future Work

8.1 Kinematics

Aldebaran documentation provide the inertial matrix of each of the solids in the Nao along with their respective masses and centre of masses. Theoretically, it should be possible to calculate the robot's momentum along each of its limbs. This could be beneficial for dynamic balancing, improving both walks and kicks.

Currently, kinematics and the Pose are used to estimate the distance to objects seen on the field. However, this is subject to inaccuracies in sensor data such as the body lean. While the body lean has significantly improved field point location estimation, multiple degrees of uncertainty are introduced as the calculations travel up the kinematics chain. As such, another option is to bypass kinematics altogether. Instead, to calculate the distance to objects on the field, it is possible to use the distance from the body or the feet as seen by the camera and process the data using vision.

8.2 Walking and Kicking

One of the major improvements to add to the walk is the inclusion of the centre of mass and its velocity. In fact, development has already begun into such a walk, which should hopefully be more smoother and more reactive as a result. Ideally, incorporating the centre of mass and its imbalance across the robots' coronal plane should help correct their tendencies to veer towards the right. This addition would also be useful for dynamic balancing during kicks.

The lack of power in the right foot kicks is also of notable concern. Perhaps the joint values or periods should be tweaked, as currently a lot of the striker's versatility is lost when it is limited to lining up big kicks with the left foot. Ideally however, a powerful and efficient kick motion could be learnt with machine learning.

Dribbles should be better integrated with walks, much like the forward shuffle in the PlannedWalkGenerator as created in 2012. In particular, the completion of an integrated sideways shuffle would further power rUNSWift's agility on the field.

Dynamic and reactive motions were only just begun to be touched upon in 2012, with much more room for expansion. Instead of the turn step being specifically for turning, it too could become an omni step - fine tuned to move forward, left, and turn depending on where the robot should kick. In a sense, this last step could be accurately carried out in the walk engine and replace the need to line up at the ball. Currently such a system is only applied to kicks, however there is much potential for their use in dribbles and shuffles as well.

This approach could be further expanded to concepts beyond stepping. For example, the period of the turn step and coronal rock could be varied depending on the angle requested, allowing faster kick times for smaller angles. Reactive adjustments of the rock would also improve the kick's balancing and hence success, as well as save developer time spent on manually tuning and hard coding constants.

8.3 Getup Routines

Considering the aggressiveness of rUNSWift's play and walk, a dynamic get up could be very useful for ensuring the robots' continued presence in the game. By incorporating sensor data such as the body lean as opposed to simply following a set of joint values from a static pos file, fallen robots would ideally be able to react to nearby obstacles. For example, if another robot was in the way preventing the completion of an arm swing off the ground and this problem was detected, it could respond by using the opposite arm, or attempting to repeat just that movement.

8.4 Striker Behaviour

Although the kick off strategy was usually quite effective, there are still many areas for improvement. Currently the strategy is hard coded and cannot be changed mid-game without calling a time-out or waiting for half time, and would not be tested before its use. Instead, it could be made more dynamic by using robot detection to figure out the most empty areas of the opponent's half, and kick off the ball in that direction.

Finally, while the current illegal defender behaviour does prevent penalties, it is not always the best solution. For example, if it was on the side of the goal box and the ball was on the opposite side, still not within the illegal defender area, the striker would be unable to get to the ball. It would either walk through the goal box to get to the ball without any kind of intelligent pathing, or patter on the spot in its illegal defender behaviour. Ideally, obstacle avoidance could be reused like it had in WalkToPoint [30] to walk around the edges of the goal box.

Chapter 9

Conclusion

The main motivation behind this thesis was to create an omnidirectional kick, and then apply it to the Aldebaran Nao in particular. The final intention was to use this new technique in rUNSWift's striker robot to improve competition results at the annual Robocup Standard Platform League.

To implement such a kick technique, one first had to consider all the aspects of balance, accuracy, speed and reliability. As such, this led the first development cycle through the kinematics module, where important characteristics of the robot, such as its centre of mass and body lean, were applied to achieve a more accurate understanding of the robot's pose. Subsequently, the dynamic omnidirectional kick was formed within the kick engine with quicker aim and increased power for churning out the goals. By first taking a step to turn and then reusing the forward kick, omnidirectionality was achieved without the need for the manipulation of the hip yaw pitch joint and without any loss of power. This was supplemented by the dribble kicks, which were integrated with the walk for additional speed and manoeuvrability at the cost of distance and power. Additional motion changes were made to the front getup routines to improve its reliability with new inwards arm swings. Finally, the work presented in this thesis, along with the contributions of fellow members in the other rUNSWift modules, was culminated in the striker behaviour with significant reductions in line up and goal scoring times.

As the results have shown, these efforts were ultimately successful as rUNSWift performed extremely well in Robocup Standard Platform League during 2012. Although rUNSWift's final placement was third, competition was extremely close and reflected the advancements in the levels amongst several top teams in just the past year. While the state of competition is still far from the league's ultimate goal of challenging human soccer players by 2050, it is continuing to improve every year.

Bibliography

[1] "RoboCup Standard Platform League." Available online: `http://www.tzi.de/spl/`.

[2] "Aldebaran Robotics Nao." Available online: `http://www.aldebaran-robotics.com/en/`.

[3] T. Matsubara, J. Morimoto, J. Nakanishi, S.-H. Hyon, J. G. Hale, and G. Cheng, "Learning to Acquire Whole-Body Humanoid Center of Mass Movements to Achieve Dynamic Tasks," *Advanced Robotics*, vol. 22, no. 10, pp. 1125–1142, 2008.

[4] B. Jalgha, D. C. Asmar, and I. H. Elhajj, "A hybrid ankle/hip preemptive falling scheme for humanoid robots," in *ICRA*, pp. 1256–1262, IEEE, 2011.

[5] M. E. Abdallah and A. Goswami, "A Biomechanically Motivated Two-Phase Strategy for Biped Upright Balance Control," in *ICRA*, pp. 1996–2001, IEEE, 2005.

[6] T. F. Yik, "Locomotion of bipedal humanoid robots: Planning and learning to walk," Master's thesis, The University of New South Wales, 2007.

[7] S.-J. Yi, B.-T. Zhang, D. Hong, and D. D. Lee, "Online learning of a full body push recovery controller for omnidirectional walking," in *Humanoids*, pp. 1–6, IEEE, 2011.

[8] C. J. C. H. Watkins and P. Dayan, "Q-learning," *Machine Learning*, vol. 8, no. 3-4, pp. 279–292, 1992.

[9] T. Röfer, T. Laue, J. Müller, A. Fabisch, F. Feldpausch, K. Gillmann, C. Graf, T. J. de Haas, A. Härtl, A. Humann, D. Honsel, P. Kastner, T. Kastner, C. Könemann, B. Markowsky, O. J. L. Riemann, and F. Wenk, "B-Human Team Report and Code Release 2011." Available online: `http://www.b-human.de/downloads/bhuman11_coderelease.pdf`, 2011.

[10] C. Graf and T. Röfer, "A Closed-loop 3D-LIPM Gait for the RoboCup Standard Platform League Humanoid," in *Proceedings of the Fifth Workshop on Humanoid Soccer*

Robots in conjunction with the 2010 IEEE-RAS International Conference on Humanoid Robots, (Nashville, TN, USA), 2010.

[11] C. Graf, A. Härtl, T. Röfer, and T. Laue, “A Robust Closed-Loop Gait for the Standard Platform League Humanoid,” in *Proceedings of the Fourth Workshop on Humanoid Soccer Robots in conjunction with the 2009 IEEE-RAS International Conference on Humanoid Robots*, (Paris, France), pp. 30 – 37, 2009.

[12] C. Graf and T. Röfer, “A Center of Mass Observing 3D-LIPM Gait for the RoboCup Standard Platform League Humanoid.” Available online: `www.informatik.uni-bremen.de/kogrob/papers/RC-Graf-Roefer-11.pdf`, 2011.

[13] H. Akin, T. Mericli, K. Özkucur, and B. Gökce, “Cerberus 2010 team description paper.” Available online: `http://www.tzi.de/spl/pub/Website/Teams2009/Cerberus10TDP.pdf`, 2010.

[14] R. Tilgner, T. Reinhardt, D. Borkmann, T. Kalbitz, S. Seering, R. Fritzsche, C. Vitz, S. Unger, S. Eckermann, H. Mller, M. Bellersen, M. Engel, and M. Wnsch, “Nao Team HTWK Leipzig Team Research Report 2011.” Available online: `http://robocup.imn.htwk-leipzig.de/documents/report2011.pdf`, 2012.

[15] M. Karamitrou, N. Kofinas, N. Pavlakis, A. Topalidou-Kyniazopoulou, A.-D. Tzanetatou, N. I. Spanoudakis, and M. G. Lagoudakis, “Kouretes 2012 SPL Team Description Paper.” Available online: `http://www.intelligence.tuc.gr/kouretes/docs/2012-kouretes-nao.pdf`, 2012.

[16] A. Ratter, B. Hengst, B. Hall, B. White, B. Vance, C. Sammut, D. Claridge, H. Nguyen, J. Ashar, M. Pagnucco, S. Robinson, and Y. Zhu, “rUNSWift Team Report 2010 Robocup Standard Platform League.” Available online: `http://www.cse.unsw.edu.au/~robocup/2010site/reports/report2010.pdf`, 2010.

[17] J. Müller, T. Laue, and T. Röfer, “Kicking a Ball - Modeling Complex Dynamic Motions for Humanoid Robots,” in *RoboCup 2010: Robot Soccer World Cup XIV*, vol. 6556 of *Lecture Notes in Artificial Intelligence*, pp. 109–120, Springer; Heidelberg; http://www.springer.de/, 2011.

[18] Y. Xu and H. Mellmann, “Adaptive motion control: Dynamic kick for a humanoid robot,” in *Proceedings of the 33rd Annual German Conference on Artificial Intelligence (KI 2010)*, vol. 6359, pp. 392–399, Springer Berlin / Heidelberg, 2010.

[19] M. Hausknecht and P. Stone, "Learning Powerful Kicks on the Aibo ERS-7: The Quest for a Striker.," in *RoboCup* (J. R. del Solar, E. Chown, and P.-G. Plger, eds.), vol. 6556 of *Lecture Notes in Computer Science*, pp. 254–265, Springer, 2010.

[20] Y. Tanaka, M. Shiokawa, H. Yamashita, and T. Tsuji, "Manipulability Analysis of Kicking Motion in Soccer Based on Human Physical Properties," in *IEEE International Conference on Systems, Man, and Cybernetics*, (Taipei, Taiwan), 2006.

[21] D. Collien and G. Huynh, "From AIBO to Nao - The Transition from 4Legged to 2Legged Robot Soccer," Undergraduate Honours Thesis, The University of New South Wales, 2008.

[22] A. Tay, "Walking Nao Omnidirectional Bipedal Locomotion," Undergraduate Honours Thesis, The University of New South Wales, 2009.

[23] B. White, "Humanoid Omni-directional Locomotion," Undergraduate Honours Thesis, The University of New South Wales, 2011.

[24] R. Liu, "Bipedal Walk and Goalie Behaviour in RoboCup SPL," Undergraduate Honours Thesis, The University of New South Wales, 2012.

[25] S. Harris, "Efficient Feature Detection Using RANSAC," Undergraduate Honours Thesis, The University of New South Wales, 2011.

[26] A. Robotics, "NAO Motors and Kinematics." Available online: `http://www.aldebaran-robotics.com/documentation/nao/hardware/kinematics.html#hardware-kinematics`, 2012.

[27] "Recapitulation of DH convention." Available online: `http://runswift.cse.unsw.edu.au/confluence/download/attachments/3047453/modified-dh.pdf?version=1&modificationDate=1266233105592`.

[28] "Nao Forward Kinematics: Leg To Camera." Available online: `http://runswift.cse.unsw.edu.au/confluence/download/attachments/3047440/100215-NaoForwardKinematicsLegToCamera.pptx.pdf?version=2&modificationDate=1266227985534`.

[29] R. T. Committee, "RoboCup Standard Platform League (Nao) Rule Book." Available online: `http://www.tzi.de/spl/pub/Website/Downloads/Rules2012.pdf`, 2012.

[30] R. Roy, "Low Level Behaviours For Soccer-Playing Robots," Postgraduate Research Project, The University of New South Wales, 2012.

[31] Y. Hunter, "Humanoid Robot Localisation for the RoboCup Standard Platform League," Undergraduate Honours Thesis, The University of New South Wales, 2012.

[32] P. Anderson, "New Methods for Improving Perception in RoboCup SPL," Undergraduate Honours Thesis, The University of New South Wales, 2012.

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