CHAPTER 2 - LITERATURE REVIEW

2.1. Similar Works

This section presents some literature regarding works related to different kinds of quadrupedal robot.

2.1.1. SCOUT-1 Quadruped Robot

Buehler et al. [2] introduced SCOUT, a quadruped robot with a very simple mechanical design which implemented only one degree of freedom for each leg [2]. Working based on controlled momentum transfer, SCOUT managed to perform gaits such as walking, turning, and step-climbing even though its mechanical structure is relatively uncomplicated compared to other quadruped robots. The particular research done in [2] explored the possibility of reducing cost and improving reliability of legged robot application while maintaining the main importance of functionality.

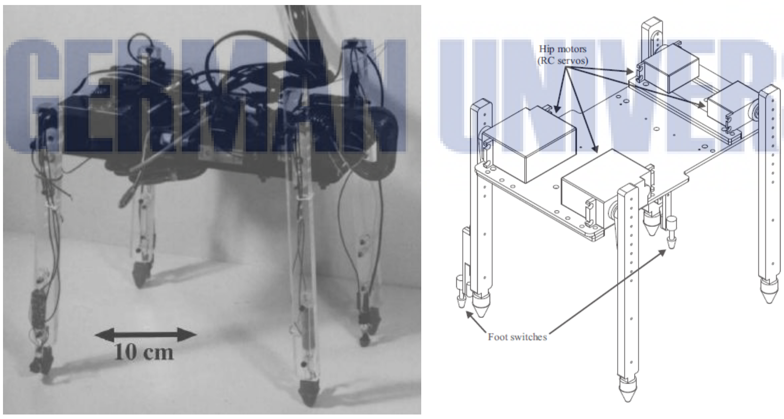

Figure 2.1. SCOUT-1 Quadruped Robot [2]

2.1.1.1. Mechanical Structure of SCOUT-1 Quadruped Robot

The purpose of the researchers of SCOUT-1 was to propose a new class of quadruped robots which concentrates on mechanical simplicity. Its four legs are plain rigid bars without any further segmentation. Each of the legs is actuated by a servo at the hip joints of the robot. As the body of the robot is a single platform containing the four hip servos.

2.1.1.2. Modeling and Control Strategy of SCOUT-1 Quadruped Robot

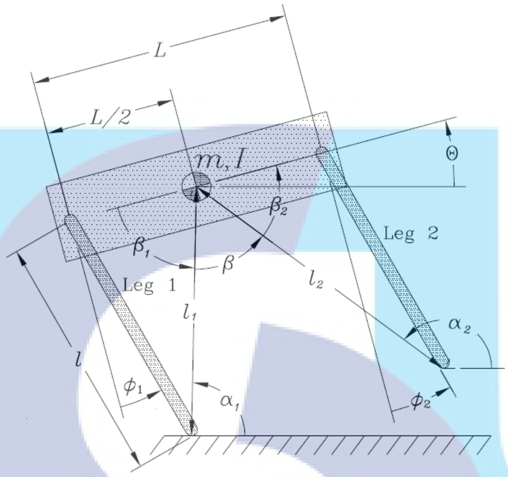

Figure 2.2. SCOUT-1 Kinematic Model [2]

Figure 2.2 shows the kinematics model of SCOUT-1 Quadruped Robot as found in [2]. Slip is considered insignificant, thus the contact between the leg and the ground is modeled as a free pin joint. The mass and inertia of the legs are neglected, since they are considered to be small compared to the mass and inertia of the body. The input to the controller is either input torques to the hip joints, or hip angles and velocities; while the outputs are the controlled body angle and velocity just after impact.

Momentum transfer occurs at the moment one of the legs touches the ground, altering the linear and angular velocities of the robot. The impact when the legs touch the ground is assumed to be inelastic and happening only at an instance. Therefore, using the principle of conservation of angular momentum with respect to the touchdown toe, the changes of those velocities can be calculated.

2.1.1.3. Performance of SCOUT-1 Quadruped Robot

Five different kinds of gait were evaluated by Buehler et al.: walking, turning, step climbing, stair climbing, and running.

Even without any stabilizing feedback implemented, the walking gait of SCOUT-1 was stable despite facing severe perturbations. Turning gait of the robot was capable of making a 90 degree of turn in four steps. The robot was also able to climb onto a step which heighted 45% of the robot's leg length. While for simulating stair climbing, SCOUT-2 was used instead of SCOUT-1. This was due to the small size of SCOUT-1, which made it difficult to climb full size stairs with depth of 25 cm and rise of 20 cm. The control was similar with step climbing. Finally, even though SCOUT-1 had no linear leg actuators, the hip actuators were able to control the hopping height, forward speed during flight via adjusting the touch-down angle, and the body attitude during stance for performing the running gait.

According to Buehler et al. in [2], the advantages of SCOUT-1 are its capability of providing a rich set of behaviors (including walking, turning, step climbing, stairs climbing, and running) despite its mechanical simplicity. The researchers hoped that SCOUT-1 would open new opportunities for legged robots with simplicity, potential low cost, and mechanical robustness to be used in practical applications.

2.1.2. SCOUT-2 Quadruped Robot

Figure 2.3. SCOUT-2 Quadruped Robot [3]

Talebi et al. introduced SCOUT-2 [3] as the second generation of SCOUT. SCOUT-2 is an autonomous quadruped robot with only one actuator per compliant leg. The purpose of the research concluded by Talebi et al. in [3] was to show that dynamic running is possible with a very simple control strategy.

Continuing the progress of SCOUT-1, the stiff legs of SCOUT-1 were replaced by compliant legs. Compliant prismatic joint was added to each leg. A new, simple running controller with minimal feedback was developed and furthermore proved that dynamic stability can be achieved via simple control laws.

2.1.2.1. Mechanical Structure of SCOUT-2 Quadruped Robot

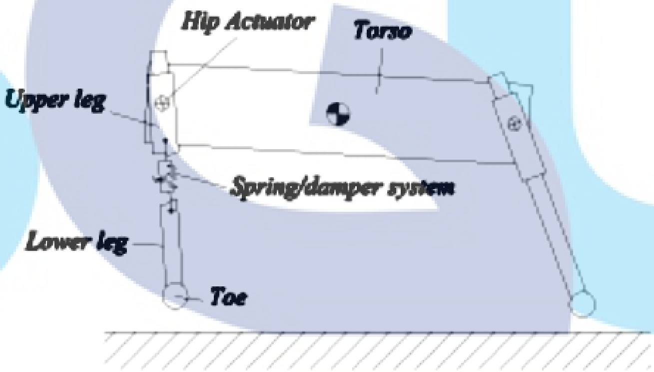

Figure 2.4. SCOUT-2 Mechanical System [3]

The spotlight features of the mechanical design of SCOUT-2 are single actuator and compliant prismatic joint for each leg. The actuators are revolute hip joints. They are placed on the body of the robot, and every leg is attached to one actuator.

The sagittal diagram of the mechanical system of SCOUT-2 is shown in Figure 2.4, as illustrated by Talebi et al. in [3]. Each leg consists of an upper part and a lower part. They are connected via a spring-damper system acting as a compliant prismatic joint. This enables the length of the leg to change passively when the tip of the leg touches the ground. When a particular leg is in its flight or swing phase, the length of the leg is maximum. However, when the leg is in contact with the ground in its stance phase, the lower part slides into the prismatic joint, compressing the spring. As the result, the overall leg length decreased due to the load on the spring. After the leg leaves the stance phase, the compressed spring will extend the leg back to its relaxed position.

2.1.2.2. Modeling and Control Strategy of SCOUT-2 Quadruped Robot

SCOUT-2 moves by means of bounding gait, which means that the legs are paired into front and back pairs of legs. A five-body kinematic chain (composed of a torso, the upper part of the front pair of legs, the upper part of the back pair of legs, the lower part of the front pair of legs, and the lower part of the back pair of legs) is used for modeling the motion of SCOUT-2. Each pair of legs is modeled as a single virtual leg, since the motions of paired legs are expected to be identical in bounding gait.

There are four robot states: front flight-back stance, front stance-back flight, double flight and double stance.

SCOUT-2 has an open-loop control. Legs are simply fixed at a certain angle while the particular legs are in flight to reach the desired touchdown angle. During stance phase, the maximum allowable torque of the hip motor is applied until the leg exceeds a specific angle limit, then the angle limit is maintained until the end of stance. The controller is an independent leg controller, and there is no actively controlled coupling between the fore and hind limbs.

2.1.2.3. Performance of SCOUT-2 Quadruped Robot

Interestingly, the simple control laws of SCOUT-2 succeeded in achieving stable periodic motions and resulting in robust and fast running. The bounding controller managed to provide stable and robust bounding at top speeds between 0.9 and 1.2 m/s without feedback of forward velocity or body angle. Talebi et al. had successfully shown in [5] that a very simple control strategy is adequate for dynamic running on compliant quadruped robot.

2.1.3. Cheetah-cub Quadruped Robot

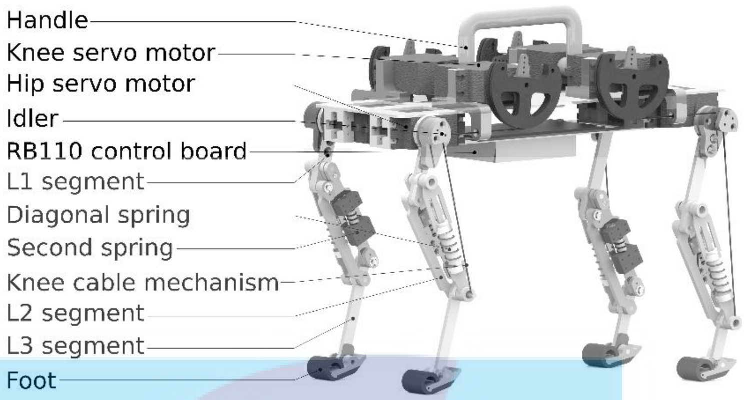

Figure 2.5. Cheetah-cub Quadruped Robot [1]

Cheetah-cub [1] was developed to be a fast, dynamic trotting quadruped robot based on a spring-loaded, pantograph mechanism with multiple segments. The focus of the research conducted in [1] was to identify the main building blocks of the Cheetah-cub robot, both at the level of hardware and control, to reach closer to what nature demonstrated already on feline morphological structure. The implementation of multi-segment, compliant legs presents a major biological solution to cover large distances, cross rough terrain, swim, climb trees, accelerate and decelerate swiftly, change directions, change gait and run energy efficiently, or jump.

2.1.3.1. Mechanical Structure of Cheetah-cub Quadruped Robot

The leg configuration of Cheetah-cub quadruped robot is based on a spring-loaded, pantograph mechanism with multiple segments. Dimensioning of the robot is also done roughly based on the segment length ratios per full leg length for felines. They include a gravity-loaded leg spring to represent the muscle on limbs of animals. There are two actuators: hip actuator at the hip joint and knee actuator mounted proximally on the robot chassis, but connected to the knee joint via Bowden cable mechanism. The role of the knee actuator is only to retract the leg (by pulling on a cable) and not to extend the leg (leg extension is solely due to the springs).

Two leg designs are proposed by Sprowitz et al. in [1]: *spring loaded pantograph* leg (SLP-leg) and *advanced spring loaded pantograph* leg (ASLP-leg). The illustration of them is shown by Figure 2.6.

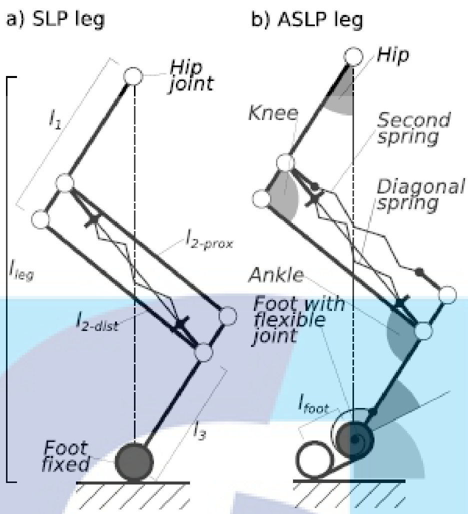

Figure 2.6. Schematic of SLP-leg (left) and ASLP-leg (right) of Cheetah-cub Quadruped Robot

2.1.3.2. Modeling and Control Strategy of Cheetah-cub Quadruped Robot

The running trot mechanism of Cheetah-cub is based on joint-space and open-loop, rhythmic locomotion patterns. The idea is that relatively simple tasks such as rhythmic locomotion on flat terrain should be performed almost “blindly” without the need for sensory feedback or an explicit model of the robot [1].

Central Pattern Generator is applied to easily parameterize and synchronize a set of open loop trajectories. A node in the form of an oscillator represents each leg of the quadruped robot. The oscillator contains two state variables: one being the angular position setpoint of the hip joint and the other corresponding with the phase of the leg (swing or stance phase). These oscillators are coupled together using coupling matrices, which values show the relations among the legs on gait characterized by the matrices.

While the angular position profile of the hip joint is determined by the implemented Central Pattern Generator, the knee joint angle profile is adjusted using a piecewise cubic profile. The plotted result of open loop trajectories for one stride cycle of the robot revealed in [1] is shown on Figure 2.7.

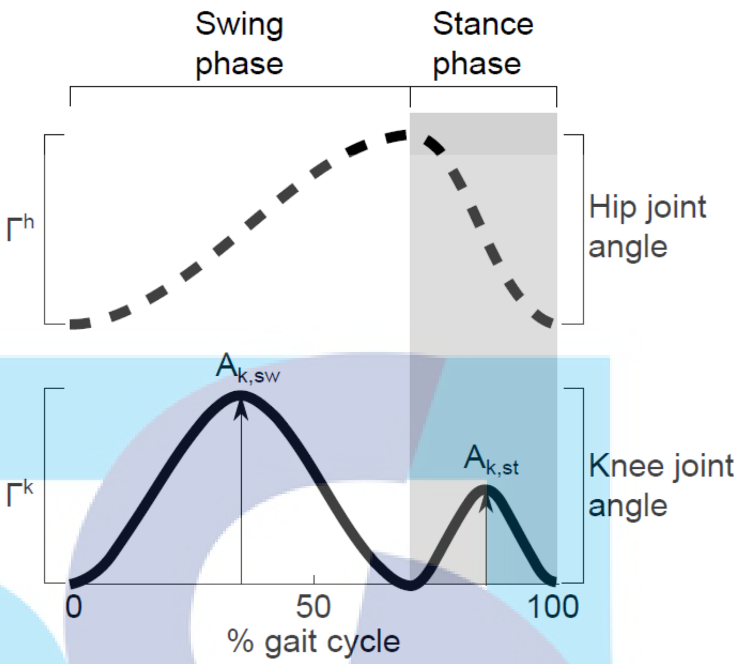

Figure 2.7. One Stride Cycle Trajectories of Cheetah-cub Quadruped Robot

2.1.3.3. Performance of Cheetah-cub Quadruped Robot

The robot reached a running trot with short flight phases. According to the result presented, Cheetah-cub is able to speed up to 1.42 m s^{-1}, corresponding to a Froude number of FR = 1.30 or v = 6.9 body lengths per second. Due to a compliant robot design, the robot itself gains self-stabilizing properties, that sensory feedback is unnecessary. When it encountered perturbations at high speed such as a step-down, the success rate of passing the obstacle was between 80% and 20%, depended on the height of the step down, with step-down heights up to 20% of the standing leg length.

Sprowitz et al. stated in [1] that, especially when compared to larger and stiffer quadruped robot designs, the Cheetah-cub has several advantages:

- It is the fastest of all quadruped robots below 30 kg in terms of Froude number and body lengths per second

- It shows self-stabilizing behavior over a large range of speeds with open loop control
- It is light-weighted, compact, electrically powered
- It is cheap, easy to reproduce, robust, and safe to handle

However, as a quadruped robot the current version of the Cheetah-cub was successful only on flat terrain, which is a big loss since the purpose of maintaining the gait complexity of legged robot is enabling the robot to conquer rougher terrain.

2.1.4. Comparison Table of the Evaluated Quadruped Robots

Table 2.1 lists the different features of the aforementioned quadruped robots in Section 2.1.1, 2.1.2 and 2.1.3. The compared aspects are leg design, leg segmentation, active actuator, compliant component, control principle and gait type.

Table 2.1. Comparison Table of Some Quadruped Robots

Robot (Author, Year)	**Scout I (Buehler et al., 1998)**	**Scout II (Talebi et al., 2000)**	**Cheetah-cub (Sprowitz et al., 2013)**
Leg design	Stiff	Telescopic/ prismatic	Pantographic
Leg segmentation	1	2	3 (SLP-leg) or 4 (ASLP-leg)
Active actuator	Hip joint on each leg	Hip joint on each leg	Hip and knee joint on each leg
Compliant component	none	Compliant prismatic joint per leg	Compression spring(s) and torsion spring (ASLP-leg only) on each leg
Control Principle	Controlled momentum transfer	Independent bounding leg controller with PD control	Central Pattern Generator
Gait type	Bounding	Bounding	Trotting

2.2. Theoretical Perspectives

The following explanation concludes the related theorem which were implemented on this research.

2.2.1. Quadrupedal Gaits

Legged robots are usually locomoted by means of periodic leg motions. The motions of four-legged robots, or also known as quadrupedal robot, are generally adapted from the gait of four-legged animals such as horse. Figure 2.8 illustrates the walking gait of a horse. Contact between the legs and the ground enables reaction force of the ground to move the mass center of the robot. Varieties of possible leg cycles result on diverse range of possible forms of motion.

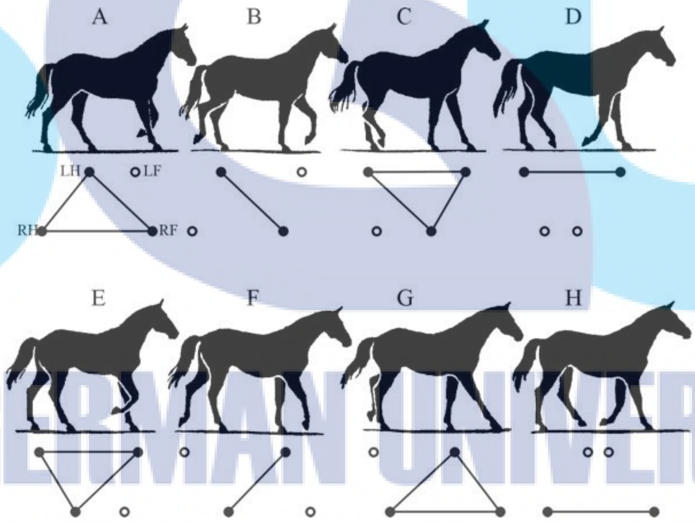

Figure 2.8. Illustration of Horse Walking Gait

Some common gaits of quadrupedal robot are stated by Collins and Richmond in [4]. These gaits are walking, trotting and bounding. Walking gait has phase offset differences of a quarter period among the limbs: front-left, hind-left, front-right and hind-right in descending order (the most leading to the most lagging). Trotting gait has one pair of diagonal limbs moving in a phase, while the other pair differs by a half period. Finally, bounding gait has similar phase differences as trotting gait, but the limbs are paired front-to-front and hind-to-hind instead of diagonally paired.

2.2.2. Stride Cycle of Cat

Stride cycle of cat may be divided based on the existence of contact between the foot with the ground into swing and support (stance) phases. While the leg is in the swing phase, the leg is expected to be swinging on the air, not touching the ground. On the contrary, in the stance phase the particular leg should be stepping flat on the ground. Transition from stance phase to swing phase is indicated by the occurrence of toe-off—the leg position when the tip of the leg is just about leaving the ground. Its counterpart, the transition from swing phase to stance phase, is shown by the occasion of touch-down—the leg position when the foot-toe segment is just positioned flat on the ground. As the summary, the sequence of one quadruped leg stride cycle consists of toe-off, swing phase, touch-down, and stance phase. The sequence repeats as the cycle continues. It has been observed by Halbertsma in [5] that the sequence of events in the cycle almost has no differences even when there is change in locomotion speed or gait.

It is going to be shown on Section 3.1.1 that stride cycle of the quadrupedal robot will be defined by a set of pre-determined joint angle profiles, consisting of hip and knee joint angle profiles. It is decided to adopt sinusoidal plot of these profiles, based on the experiment results presented in [5] by Halbertsma. Halbertsma through his work has done some observations on the stride cycle of cat, including surveillance on stride at different velocities of locomotion, relation between electromyography activity and movements, the positioning of the foot at touch-down and lift-off, and adaptation of limb movements during split belt locomotion. Through qualitative comparison on the experiment data, the hip and knee joint angle profiles have the common trend of resembling sinusoidal wave.

2.2.3. Dynamic Treatment of Legged Locomotion

Raibert [6] stated that behavior of a dynamic system is predicted and influenced by considering the accumulated energy in every mass and spring included in the system, plus geometrical constrains and mechanism arrangement. Understanding the exchange of energy and motion sequence of the system is also claimed to be substantial in comprehending legged locomotion.

Despite the complex dynamics of a legged system, the control techniques which use dynamics are not necessarily as complicated. Raibert in [6] had hopping motion as his example. Hopping as a reverberating bouncing motion does not need any trajectory control, but instead produced by a thrust of the right magnitude delivered only once per cycle. The control system then can focus more on generating the right mechanism.

Static balancing attempts to maintain the center of mass of the body so that its position remains inside the support polygon formed by the supporting feet. This support relationship is to be kept all time. Referring to the usage of static balancing in the nature, Raibert declared that animals occasionally balance statically when moving slowly, but balancing dynamically is more common.

Applying dynamic balancing on a legged system enables the system to tip, bounce and accelerate for short instances instead of constantly work around equilibrium. The purpose of the control system used is then ensuring that 1) the imbalance of the system for each cycle is concise, and that 2) inclination towards a particular direction is offset by another inclination towards the opposing direction. However, it is to be noted that the step rate of the legged system is required to be higher than the tipping rate.

2.2.4. Mechanical Torque Calculation

Calculation of mechanical torque is done by using the equation for calculating moment of a system consists of interconnected bodies about an arbitrary point P for rigid-body plane motion, as adapted from the one stated by Meriam and Kraige in [7]:

$$\Sigma M_P = \Sigma \bar{I}\alpha + \Sigma m\bar{a}d \quad \text{Eq. (2.1)}$$

where ΣM_P is the total moment of the system about the arbitrary point P, $\bar{I}$ is the mass moment of inertia about an axis through the center of mass of the particular body, α is the angular acceleration of the body, m is the mass of the particular body, $\bar{a}$ is the acceleration of the particular body, and d is the perpendicular distance from P to the center of mass of the particular body.

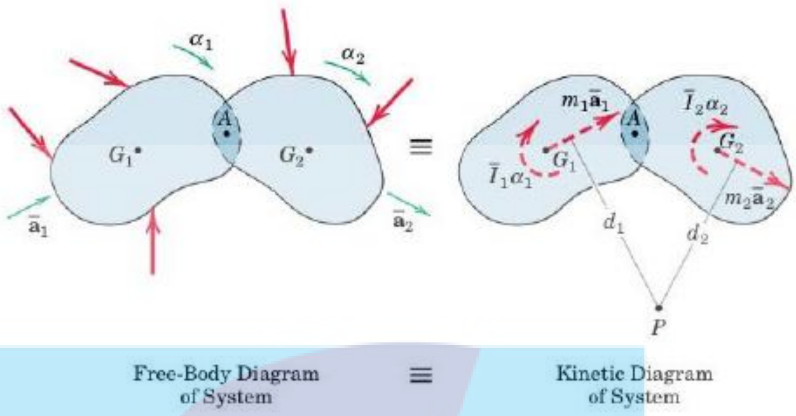

Figure 2.9. Systems of Interconnected Bodies [7]

2.2.5. Smart Servo Motor

Among various kinds of actuation system, electrical actuation system which is supplied with d.c. voltage may be considered the most practicable solution for driving mobile robots. D.C. motors, commonly powered by batteries on a mobile robot, produce rotation as electric current flows through the motors. The speed of the rotation depends on the current supplied to the motor, but generally the speed control is done by controlling the voltage applied to the armature coil inside the motor.

The usage of fixed voltage supplies is regarded as more feasible on most application, thus electronic circuit is employed to obtain variable voltage. However, since driving d.c. motors is often done by means of controlling signals emitted by microprocessors, a technique called pulse width modulation (PWM) is usually used. The voltage supplied to the motor is periodically switched on and off alternately at a certain duty cycle period so that the average voltage value is varied [8].

For the purpose of motion control, d.c. stepper motors and d.c. servo motors are regularly implemented. Stepper motors are rotated partially on a fixed fraction depending on their digital pulses input. They are considered as reliable enough for applications in which rapid acceleration and high speed are not necessary, while partial position accuracy at certain setpoints is already adequate. More precise positioning is featured on d.c. servomotors. Higher speeds and smoother low-speed operation with finer position resolution than that of d.c. stepper motors are achievable on d.c. servo motors, but they are usually more expensive.

Both d.c. stepper motors and d.c. servo motors are sometimes complemented with additional feedback sensors, such as rotary encoders, incremental encoders, absolute encoders, magnetic encoders and potentiometers. Their purpose is increasing the accuracy in correcting velocity and position errors [9].

A relatively new generation of d.c. servo motors, Smart Servo Motors, are considered as smart actuators since they include internal sensors and have their own internal control algorithm handled by built-in microcontroller. The advantage of these smart servo motors is simplification of the whole system, since the control of these servos and feedback retrieval from the servos are done by transmitting and receiving certain data packet through communication bus.

Figure 2.10. Dynamixel AX-12A (left) and HerkuleX DRS-0101 (right)

Two examples of smart servo motors are Robotis Dynamixel AX-12A and Dongbu HerkuleX DRS-0101. Both types are quite similar in terms of dimension, weight, resolution, variety of feedback, and availability of library for controlling the servos. However, Dynamixel and HerkuleX servos differ by their communication protocol. Dynamixel servos use Multi-Drop TTL Half-Duplex UART Serial Communication Protocol, while Herkulex servos use Multi-Drop TTL Full-Duplex UART Serial Communication Protocol.

2.2.6. Microcontroller Board

The usage of microcontroller board as controller hardware for different kinds of robotic application has become common. The reason is that microcontroller boards already contain general-purpose microprocessor, Input-Output (I/O) ports, timer or clock generator, Random Access Memory (RAM), Read-Only Memory (ROM), communication port and any other necessary Integrated Circuit (IC), all built on a single circuit board. The general-purpose feature of the microprocessor on the board enables the users of the microcontroller board to implement their own control program which is specific to their needs. Therefore, the microcontroller board can be used immediately by an application developer.

One of the most popular microcontroller boards nowadays is Arduino board. Wide range of Arduino boards is available with various specifications. As a general purpose embedded system, Arduino board already includes internal voltage regulator, analog input-output and digital input-output, PWM generators, and communication ports in addition to the main processor chip. As an open-source platform, there are wide varieties of libraries on the Internet for the purpose of integrating different electrical components to the Arduino board.

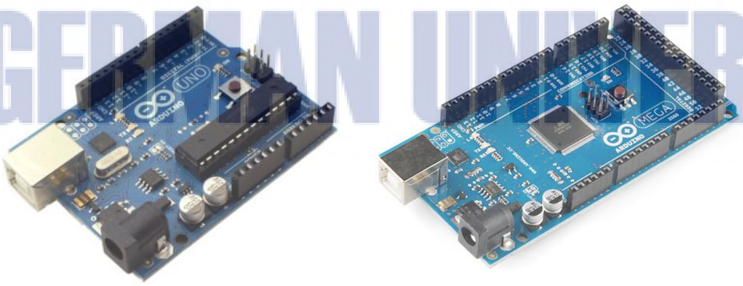

Figure 2.11. Arduino UNO (left) and Arduino Mega 2560 R3 (right)