Parent Controller	Child Controller	Communication
L3 Process Controller	L2 Clamp Controller	Custom, G-Code-like Commands, communicated over ROS via roslibpy via ros_bridge
L2 Clamp Controller	L1 Clamp Firmware	Custom, G-Code-like Commands over custom radio wireless network *(see 5.3.9 CL3 Firmware)*
L3 Process Controller	L2 ROS-RRC Driver	Instructions implemented in compas_rrc, communicated over ROS via roslibpy via ros_bridge
L2 ROS-RRC Driver	L2 RRC Server	Protocol implemented in compas_rrc over ROS

Detail Level	Property
Joint Level	Joint Geometry / Joint Assembly Direction / Geometrical blocking direction
Beam Level	Beam Assembly Direction
Global / Assembly Level	Assembly Sequence / Order of Assembly
Global / Assembly Level	Geometrical Arrangement / Neighbour Relationship

	Linear Motion (LM)	**Free Motion (FM)**
End Effector and Workpiece Movement	Straight-line motions between two points.	Typically only the start and end positions are constrained. The in-between path is free for the planner to decide.
Reasons for their use	LM belongs to a class of constrained motion. They are used when the exact motion path is known, such as when performing some insertion or sliding movement. Note that even though the path of the end-effector is fixed, the movement of each joint is still free for the planner to decide. For high DOF robots, this can allow the robot body to move around obstacles.	FM allows the planner to find a valid path around obstacles by moving all the available joints; it is often used when a logical path cannot be easily defined.
Example	To move a beam linearly during joint closure. Because the beam's motion is constrained by the geometry of the mating timber joints.	To bring a timber beam from the pickup location to the work area through tight openings of the already assembled structure.

	Linear Motion Planner (LMP)	**Free Motion Planner (FMP)**
Planning Approach	**Sample and projection technique**	**Sampling-based motion planning**
Algorithm used in this thesis	**Randomised Gradient Descent** (Yao & Gupta, 2007) - combines random sampling with gradient-based local search, it is effective against non-convex objective functions, such as when facing obstacles and narrow passages.	**RRT-Connect** (Kuffner Jr. & LaValle, 2000) - connects two configurations in a robot's configuration space by iteratively growing two trees, one from the start and the other from the goal, and attempting to connect them at each iteration.

	Worm Gearbox 1:54	**Worm Gearbox 1:54**
Pull Force with LiPo Battery	4900N (no damage observed)	4450N (no damage observed)

Component	Specification
Radio	CC1101 by Texas Instruments, on pre-integrated PCB module
Motor Driver	H-Bridge Motor Driver XY160D
End Switch Configuration	Normal close (NC) switch
Microcontroller	Arduino Nano (ATMEL ATMEGA328 with new bootloader @ 16MHz)
Voltage Regulator	Linear Voltage Regulator Chip LM7805 with filter capacitors
Radio Addressing Switch	4 position DIP switch with resistor ladder
Battery Choice	Typical: 4-cell Li-Po 1000mAh 4S 75C (Nominal 14.8V)
Battery Connector	XT60

Task	Strategy
Real-time monitoring of the motor position.	● Current position is obtained by counting encoder signals using external interrupts of the microcontroller.
Computing the error with the intended motion profile (see 5.2.3 Synchronisation between Clamp and RFL Robot).	● Position error is monitored between current position and target position. ● Target position is computed from the motion profile.
Producing control signals to the H-bridge motor driver (see 4.3.2.2 Motor Driver) that can minimise tracking error.	● The motor control signal is a PWM signal generated by the microcontroller. ● The duty cycle of the PWM signal is determined by a PID controller monitoring the positional error.

Parameters	Values	Notes
Encoder resolution	44 pulse/revolution	36GP-555 Motor with 2 channel Hall Encoder
PWM control frequency	3921.16Hz	
PWM speed control resolution	8 bit (256 steps)	Direction is a separate bit
CW CCW Zero-crossing deadband	30 / 255	
kP	0.04 throttle/step	'throttle' is a control unit for the PWM signal after adjustment of deadband. It has a full range between -1 to +1.
kI	0.2 throttle/step/s	
kD	0.0002 throttle/step/s	
Max speed	3000 step/s	5mm/s with 4mm screw lead and 1:54 gearbox
Acceleration and deceleration	3000step/s^2	No Load conditions
Maximum tracking error	8 steps	
Error threshold for triggering a stalled stop	100 steps	Approximately 0.1 to 0.2 mm error with 4mm pitch screw

Main control loop subroutines	Description
Motor Motion Control	Runs PID control loop for motion control. Only active when there is an active motion target. There is a separate timer keeping track of the PID control frequency.
Battery Monitor	Check battery level
Read and Process Serial Command	Process command received from USB serial interface, this is used only for debugging
Read and Process Radio Command	Process command received from Radio module.
Radio	Checks if Radio is still active

Technique	Explanation	Adoption
Use lower carrier frequency	Lower frequencies generally penetrate obstacles better and are less affected by occlusion.	European ISM I band (433MHz) is selected for development as it is the lowest available frequency supported by the chip. This frequency band can be used without licence in Switzerland (cite: https://www.ofcomnet.ch/api/rir/1008/05)
Error detection and correction	Error detection algorithms, such as Cyclic Redundancy Check (CRC), and correction algorithms, such as forward error correction (FEC) or automatic repeat request (ARQ), to improve the network's resilience to noise and interference.	CC1101 supports CRC for error detection. However its support for FEC only covers fixed-length messages, which was not the option selected for this development. ARQ is implemented at the application layer in the Clamp Controller running in the PC.
Contention avoidance	Contention avoidance techniques, such as Clear Channel Assessment (CCA), can reduce the chance of contention and packet loss.	CC1101 supports CCA and is used in this development.
Spread spectrum techniques	Spread spectrum communication techniques such as frequency hopping spread spectrum (FHSS) or direct sequence spread spectrum (DSSS) can increase the network's resistance to interference and enhance signal robustness.	CC1101 supports FHSS in collaboration with suitable MCU control. However, this was not implemented in this development as it is beyond my knowledge.
Antenna design and placement	Directional antennas at the base station can focus the radio signal in the desired direction and minimise interference from other sources.	A directional antenna was considered but not adopted at the base station because other techniques were already sufficient.
Maximise power	Transmission power can be increased to improve the signal-to-noise ratio.	Following the current Switzerland Radio Interface Regulation, H-band allows 1mW effective radiated power and I-Band allows 10 mW if the duty cycle is below 10%.
Multipath network	Network topology, such as a mesh network, that allows for multiple paths between nodes, can increase redundancy and improve the network's ability to handle occlusions and interference. Dynamic routing protocols can also help in maintaining network connectivity despite changing environmental conditions.	Star network topology was chosen for its simplicity and speed. Mesh topology was considered, but the implementation is likely beyond my knowledge. If mesh is necessary, a ZigBee implementation would be more appropriate.

Component	Specification
Radio	CC1101 by Texas Instruments, on pre-integrated PCB module
Mictocontroller	Arduino Nano (ATMEGA328 with new bootloader)
Power	Powered by host PC USB Port @ 5V
Connector to Serial Radio	Phoenix Terminal Block Socket 5.08mm Pitch
Connector to IC LCD Screen	Reichelt PS Series 2.5mm Pitch 5 Pin PCB Connector (PS25/5G BR)

Role	Person	Relationship
Structure Design	Frédéric Brisson	Student (see next section)
Structural Advice	Davide Tanadini	Research Collaborator
Mechanical Design	Victor Leung Pok Yin	Author
Process Design	Victor Leung Pok Yin	Author

Combinations	Beams	Count
No Clamp (Place Beam on Ground)	b0, b1, b5, b7, b12, b14, b19, b21, b24, b28, b30, b37	12
CL3	b33, b26	2
CL3 + CL3M	b23, b27	2
CL3 + CL3	b4, b6, ~~b8~~, b9, b13, b15, b16, b17, b22, b29, b31, b25, ~~b34~~, b35, b36	15
CL3M + CL3M	b2, b3, b10, b11, b18, b20, b32, b38	8
CL3 + CL3M + CL3M	b39	1
	total	40

* The crossed out beams could not be installed by the robots and were installed manually.