Type	Robot side	Stationary Side	Purpose of Alignment	Since Dev' Phase
1	**Timber joint** on beam held by robot	**Timber joint** on the partially built timber structure	Before joint closure by clamp(s)	2
2	**Clamp** held by robot	**Clamp attachment holes** on the partially built timber structure	Before attaching clamp to partially build timber structure	3
3	**ATC (Robot Side)** on robot flange	**ATC (Tool Side) on Clamp** attached to already-build timber structure	Before docking with clamp to retrieve it after use	3
4	**Clamp** held by robot	**Tool Storage Rack** at fixed location	Before returning clamp to storage rack	3
5	**ATC (Robot Side)** on robot flange	**ATC (Tool Side) on Clamp on Tool Storage Rack** at fixed location	Before retrieving clamp from storage rack	3
6A	**Screw Tip on Screwdriver** held by robot	**Pre-drilled Screw Hole** on beam with the rest of partially built timber structure	Before joint closure by screwdriver(s)	4
6B	**Screw Tip on Screwdriver attached to flying beam** held by robot			
7	**ATC (Robot Side)** on robot flange	**ATC (Tool Side) on Screwdriver** attached to already-build timber structure	Before docking with screwdriver to retrieve it after use	4
8	**Screwdriver** held by robot	**Tool Storage Rack** at fixed location	Before returning the screwdriver to the storage rack. *	4

* Note that the attachment of the screwdriver to the new beam is performed manually by the operator, no robotic alignment is performed.

Source of error	Dependent on Assembly State	Measurement Technique
Deviations in mechanical parts from designed form. (CAD to real error)	No	Manufacturing tolerances are typically specified during production and can be treated as an absolute deviation. Alternatively, the manufactured part can be measured with measuring tools, the measured deviation is likely to be more accurate than those specified by the drawings. Remember to take into account the measuring tool's accuracy.
Deviation of the timber parts due to cutting process	No	The absolute deviation can be based on manufacturing tolerance standards. This results in a step function. The resulting CDF should be a step function. For more accurate distribution, measurement can be performed on manufactured samples. (see later section about Estimating Deviations - Accuracy of Timber Parts)
Docking accuracy between docking adapter	No	The absolute deviation can be extracted from manufacturer specification.
Deformation of the partially built structure	State of the partial assembly, attached supports, and loads	Probabilistic structural analysis, physical measurement needed to calibrate the model. (see later section about Estimating Deviations - Deformation of Partially Assembled Structure)
Deformation of the robotic platform	Configuration of the robot, state of attached loads	Probabilistic robotic deviation analysis, physical measurement needed to calibrate the model. (see later section about Estimating Deviations - Accuracy of Robotic Platform)

* For measurements that rely on extracting the maximum deviation from tolerance standards, we can treat the resulting distribution as a step function, where the likelihood of deviation below that threshold is random.

Nature	Description	Deviation Fixed or State Dependent	Possible Source of Deviation and its Quantification Method	Estimated d and F(d) in the experiment setup (mm)
Interface	Robot to Ground Joint	Fixed	Difference between CAD Model and actual installation. Deviation can be measured by robot calibration procedure.	0.5 (1)
Part	Robot	State Dependent	Absolute accuracy of a robot with a fixed payload is often published by the manufacturer. Deformation of the robot body is dependent on pose and payload, it can be measured. *(see Section - Accuracy of Robotic Platform for details)*	5 (0.95)
Interface	Robot Flange to ATC Joint	Fixed	Adapter plate manufacturing tolerance and installation inaccuracy. Deviation can be extracted from part production tolerance.	0.5 (1)
Part	ATC (Robot Side)	Fixed	ATC repeatability between robot and tool sides. (The combined repeatability between of the two ATC sides are often published by the manufacturer in their specification sheet)	0.5 (1)
Interface	ATC Locking Interface	Fixed		
Part	ATC (Tool Side) and Gripper	Fixed		
Interface	Gripper to Beam Interface	Fixed (with locating feature) State dependent (with friction gripper)	If a mechanical locating feature is used, the deviation is related to the design of the feature. For example the mechanical fit between a locating pin and the corresponding hole. If a friction-based gripper finger is used, the deviation is related to the amount and probability that the beam will slip inside the gripper. This may be dependent on beam weight, grasp orientation and grasp eccentricity.	0.5 (1)
Part	Lap Joint on Beam	State dependent	CNC Machining inaccuracy of the joint. Tolerance is often published by the machine manufacturer. Timber deformation after machining. Tolerance is predictable according to expected moisture change and timber property. Actual characterisation can rely on statistical analysis of measured samples. *(see Section - Accuracy of Timber Parts for details)* Elastic deformation (bending) caused by self-weight and low beam stiffness. Depending on the geometry of the beam, grasp orientation and grasp distance from the beam's centre of inertia.	1 (1) 0.5 (0.95) 1 (0.95)

Nature	Description	Deviation Fixed or State Dependent	Possible Source of Deviation and its Quantification Method	Estimated D in the experiment setup (mm)
Interface	Foundation to Ground Joint	Fixed	Difference between CAD Model and actual installation. Deviation can be measured by using	0.5 (1)
Part	Temporary Foundation	Fixed	Absolute accuracy of a robot with a fixed payload is often published by the manufacturer. Deformation of the robot body is dependent on pose and payload, it can be measured. *(see Section - Accuracy of Robotic Platform for details)*	2 (1)
Interface	Partial Structure to Foundation	Fixed	Adapter plate manufacturing tolerance and installation inaccuracy. Deviation can be extracted from part production tolerance.	2 (1)
Part	Lap Joint on Partially assembled Structure	State dependent		2 (0.95)

Robot Side	Stationary Side	T (mm)	Correction Method	C_{Range} (mm)	$C_{Residual}$ (mm)	Used in Alignment Type (refer to table ...)
Timber Joint (Clamped)	Timber Joint (Clamped)	0 (Tight Fitting)	Chamfered Edge on both sides (Mid-assembly)	8	0	#1
Clamp gripper pins	Clamp attachment holes on beam	0.5	Chamfer Pins (Mid-assembly)	3	0.5	#2 (Bus Stop)
			Camera-Marker (Pre-assembly)	25	1	#2 (CantiBox)
ATC - Robot Side	ATC - Tool Side	2.0 (According to Shunk SWA-040 Spec Sheet)	None			#3 (Bus Stop), #5
			Camera-Marker (Pre-assembly)	25	1	#3 (CantiBox), #7
Tool Body	Tool Seat on Storage Rack	0	Chamfered Feature on Tool Seat (Mid-assembly)	5	0	#4, #8
Screwdriver Tip	Screw Hole on beam	1	Tapered Screw Tip and Chamfered Hole Entry (Mid-assembly)	10	1	#6A, #6B
Timber Joint (Screwed)	Timber Joint (Screwed)	0 (Tight Fitting)	Chamfered Edge on both sides (Mid-assembly)	4	0	#6A, #6B

	Pre-assembly correction type	Mid-assembly correction type
Definition	The correction starts and completes before the beginning of the next movement.	The correction happens during the next assembly movement.
Examples	Camera-marker correction for ATC docking and Clamp Attachment	All passive correction methods that rely on chamfered or tapered features
AlignmentTypes * (refer to table ...)	#2 (CantiBox), #3(CantiBox), #7	#1, #2 (Bus Stop), #4, #3 (Bus Stop), #6A, #6B, #8
Definition of C_{Range}	Max deviation that would still allow the correction mechanism to begin its correction.	Max deviation that would still allow the next movement to begin.
Definition of $C_{Residual}$	Max deviation after the correction is completed before beginning the next movement.	Deviation after correction provided by the next movement is completed.

* Alignment Type #5 did not employ any correction mechanism because the targets are repetitive and taught configurations are used.

#	Robot side (P)		Stationary Side (Q)		Allowable tolerance	Correction		
	Connectivity chain to P	**Estimation of D_P (mm)**	**Connectivity chain to Q**	**Estimation of D_Q (mm)**	**T (mm)**	**Mechanism**	**C_{Range} (mm)**	**$C_{Residual}$ (mm)**
1	• Ground • Robot • ATC • Gripper • Timber beam • **Timber joint**	5 to 20 depending on the position of joint on beam	• Ground • Temp Foundation • Partial Structure • **Timber joint**	2 to 20 depending on the stiffness of the partial structure	0 (Tight Fit)	Chamfered Joint Edges	5 / 8 (Bus Stop) 12 (Cantibox)	0
2	• Ground • Robot • ATC-R • **Attachment Pins on Clamp**	1 to 5	• Ground • Temp Foundation • Partial Structure • **Clamp attachment holes**	2 to 20 depending on the stiffness of the partial structure	0.5 (Gripper pins tolerance)	Clamp Gripper pins (BusStop) Camera + Marker (HyparHut, CantiBox)	3 (Gripper pins) 25 (Camera-Marker)	0.5 (Gripper pins) 1.0 (Camera + Marker)
3	• Ground • Robot • **ATC-R**	1 to 5	• Ground • Temp Foundation • Partial Structure • **ATC-T on Clamp**	2 to 20 depending on the stiffness of the partial structure	2.0 (ATC docking allowance)	None (BusStop) Camera + Marker (HyparHut, CantiBox)	0 (None) 25 (Camera-Marker)	Nil (None) 1.0 (Camera + Marker)
4	• Ground • Robot • ATC-R • **Clamp**	0.2 to 0.5 (Taught Config)	• Ground • **Tool Storage Rack**	0.1 to 0.3 (Stationary)	5 (Storage Rack Allowance)	None	Nil	Nil
5	• Ground • Robot • **ATC-R**	0.2 to 0.5 (Taught Config)	• Ground • **Tool Storage Rack** • **ATC-T on Clamp**	0.1 to 0.3 (Stationary)	2.0 (ATC docking allowance)	None	Nil	Nil
6A	• Ground • Robot • ATC-R • **Screw Tip on Screwdriver**	1 to 5 Depending on robot config	• Ground • Temp Foundation • Partial Structure • **pre-drilled Screw Hole**	2 to 5 depending on the stiffness of the partial structure (range smaller because HyparHut is designed to reduce deformation during assembly)	1 (End of first step) 0 (End of second step)	Tapered Screw Tip and Chamfered Hole Entry Chamfered Joint Edges	10 (Tapered Screw Tip and Chamfered Hole Entry) 4 (Chamfered Joint Edges)	1 (Tapered Screw Tip and Chamfered Hole Entry) 0 (Chamfered Joint Edges)
6B	• Ground • Robot • ATC-R • Screwdriver / Gripper • Flying Beam • **Screw Tip on Screwdriver**	2 to 15 Depending on the position of joint on beam						
7	• Ground • Robot • **ATC-R**	1 to 5	• Ground • Temp Foundation • Partial Structure • **ATC-T on Screwdriver**	2 to 20 depending on the stiffness of the partial structure	2.0 (ATC docking allowance)	Camera + Marker (HyparHut, CantiBox)	25	1.0
8	• Ground • Robot • ATC-R • **Screwdriver**	0.2 to 0.5 (Taught Config)	• Ground • **Tool Storage Rack**	0.1 to 0.3 (Stationary)	5 (Storage Rack Allowance)	None	Nil	Nil

* ATC-R stands for Automatic Tool Changer - Robotic Side
ATC-T stands for Automatic Tool Changer - Tool Side

	T (mm)	D (mm)	Limit (I) (II)	Limit (II) (III)		Observed probability of successful assembly
			$d \leq T$	C_{Range}	$C_{Range} \geq d$	
#1 Clamping Joint (No consideration of partial structure deformation)	0	7 to 40	No	8	If D < 8	Average (BusStop),
#1 Clamping Joint (Scaffolding used)	0	3 to 10	No	10	If D < 8	High (CantiBox)
#2 Attach Clamp (Gripper Pins only)	0.5	3 to 25	No	3	No	Low (BusStop)
#2 Attach Clamp (With Camera-Marker)				25	Always	Very High (CantiBox)
#3 Detach Clamp (No correction)	2.0	3 to 25	No	Nil		Very Low (BusStop)
#3 Detach Clamp (With Camera-Marker)				25	Always	Very High (CantiBox)
#4 Store Clamp	5.0	0.3 to 0.7	Yes	Nil		Always (BusStop, CantiBox)
#5 Get Clamp from Storage	2.0	0.3 to 0.7	Yes	Nil		Always (BusStop, CantiBox)
#6A Screwing Joint	0	3 to 10	No	10	Yes	Very High (HyparHut, CantiBox)
#6B Screwing Joint (Flying Beam)	0	4 to 20	No	10	If D < 10	High (HyparHut, CantiBox)
#7 Detach Screwdriver	2.0	3 to 25	No	25	Always	Very High (HyparHut, CantiBox)
#8 Store Screwdriver	5.0	0.3 to 0.7	Yes	Nil		Always (HyparHut, CantiBox)

Features to identify	**Example: Hypothetical DiRT-ified temporary scaffolding**
Task to be completed	● Provide support between two already-assembled timber elements. ○ The two elements are always joined by a planar joint. ■ No need to support non-planar joints ○ Since two elements are joined together, the addition of this scaffolding completes the third side of a rigid triangle. ● If possible, one side of the scaffolding should be able to attach to the base platform.
Flexibility of the task	● The two timber elements may be joined with different angles from 40 to 140 degrees. ● The supporting bar length is fixed (different lengths should be available in the toolset but not adjustable on each tool)
Attachment Method	● Direction of attachment is to be determined, two possibilities exist: ○ Enter from the gap between the two timber and pushed towards the timber joint. ○ Enter from the side of the two timber pieces, ● Registration features may be needed on the timber at the attachment point.
How deviation affects the attachment process	● Deviations between two beams are expected to be low because the scaffolding is attached while the weak beam is still held by the other robot. ● Deviation analysis is performed to determine the following. ○ Deviation of each attachment point from ground truth is <5mm @98% confidence. ○ Deviation between the distance of the two attachment point is <3mm @98% confidence. ● The attachment process is not expected to push incorrect structures back to correctness.

Specification	Generalised Construction Scenario	Timber Frame Construction	
	Determination of Specification	**Ideal Values**	**Used This Thesis**
Robot Payload Capacity	Depends on weight of workpiece to be lifted	100kg	60kg
Robot Wrist Torque	Depends on workpiece geometry and how it is held	1000Nm	105Nm (Joint 6) 200Nm (Joint 4, 5)
Robotic DOF	At least 4 (top down construction) At least 6 (spatial construction) 9 (Ideal)	9 (3 Cartesian + 6 Robot Joints) Refer to 5.2.2 RFL Robotic Platform	
Repeatability	Not very relevant. See Answer 5 of 10.1 Response to Research Questions		0,.06mm (Not very relevant)
Cartesian Accuracy	Depends on alignment requirements	2mm (worst case)	10mm (worst case) 5mm (typical)
Robotic Arm Reach	Depends on the assembly task. E.g. Distance of one structural bay (structural assembly), height of one floor (facade assembly)	2.5m	2.55m
Compactness	Depends on the assembly task, but in general: Wrist - Small enough to attach and retrieve tools on structure Elbow - Small enough to reach into openings of partially-assembled structure		Refer to the geometry of ABB IRB 4600-40/2.55.
Coordinate System	Fixed coordinate reference for the entire job site (especially relevant for robot platforms with mobile base). Ideally aligned with the reference used by the surveyor.		
Working Envelope of Gantry	Depends on size of the workpiece	2m offset larger than building size	1.5m offset larger than building size
DiRT Docking Adapter	Standardised docking interface include power feedthrough (see next section - Docking Adapter for details)		Schunk - SWA-040 (with pneumatic feedthrough)
Robot Impedance Control	Impedance control is useful for allowing the robot to be slightly compliant during docking and passive correction.		
Weather Protection	IP 67, rust protection on all weather exposed parts.		Not required

Property	Requirements	Purpose
Wireless Range	The system should offer an adequate communication range to cover the entire construction site.	Avoid disruption to the automatic construction process.
Energy Efficiency	Energy-efficient endpoint on the tool-side as DiRT tools rely on battery power for extended periods of time.	Extend DiRT battery operation time.
Low latency	Sufficiently low latency to ensure real-time control and monitoring of DiRT tools.	Allow quick detection and responses to emergency conditions.
High Data Rate	Sufficiently high data rates to accommodate control commands and telemetry data from all active tools.	Enable high telemetry frame rate.
Reliability	The system should maintain a stable connection in harsh and dynamic construction site environments, overcoming occlusions, radio interference, and signal degradation due to other machineries.	Avoid disruption to the automatic construction process.
Security	The system should incorporate encryption and authentication mechanisms	Protect against malicious control, eavesdropping and spoofing,
Fail-safe	The communication system and the DiRT tool controllers should be designed to be fail safe if one or more DiRT tool connections are lost during operation.	Avoid dangerous operations resulting from the loss of signal.
Cost Effectiveness	Low cost, particularly for the tool-side.	To ensure DiRT tools can be implemented with low cost.
Ease of deployment	Wireless routers or access points should be easy to install, configure, and maintain in a construction site. The number of network devices and physical wiring should be minimised.	Minimise the need for specialised technical expertise and reduce maintenance cost.
Scalability	As construction sites may require multiple DiRT tools and robotic platforms to work simultaneously, the system should be scalable without compromising performance.	Accommodate potentially many DiRT devices on-site.