Quasi-serial Manipulator for Advanced Manufacturing Systems

Bryan Kelly[a], J. Padayachee[b] and G. Bright
Discipline of Mechanical Engineering, University of KwaZulu-Natal, King George V Avenue, Durban, South Africa

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Abstract: Industrial automation has revolutionised manufacturing and the manufacturing environment. Advanced manufacturing requires a variety of different robotic manipulators for industrial applications, each with their defining characteristics. This research paper describes the differences between current industrial manipulators; it then proposes an open chain hybrid kinematic platform, consisting of closed loop parallelograms. The application of such a hybrid mechanism is apparent with material handling operations such as providing solutions for palletizing. A quasi-serial architecture was selected and its corresponding components were 3D printed. The forward kinematic equations were derived via a geometric approach. The outputs of these kinematic equations are then validated against empirical results obtained through an equivalent SolidWorks model of the robot.

1 INTRODUCTION

Modern manufacturing is highly dependent on industrial automation, specifically for menial tasks such as repetitive assembly or pick and place operations, such as packing and unpacking of pallets. Due to the high number of specialised tasks involved in these aforementioned procedures, many different varieties of industrial robots have been researched, developed and implemented into industry over the past several decades.

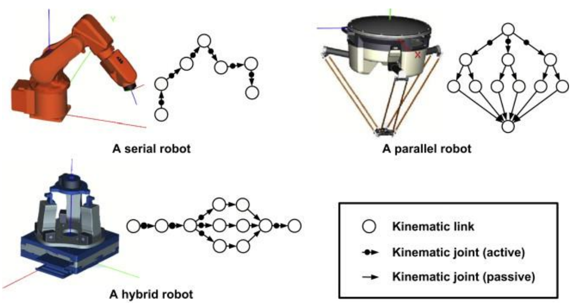

Figure 1: Industrial robot configurations. (Xiao et al., 2014).

Each of these robotic manipulators have vastly different characteristics and capabilities, depending on their defining geometric characteristics. (Pandremenos et al., 2011)

There are currently two major classifications of industrial robotic manipulator geometries, namely serial and parallel mechanisms. These different forms of manipulators have been extensively researched and tested. As a result, the advantages and disadvantages of said mechanisms are well defined. (Xiao et al., 2014)

It is now widely accepted that an open kinematic chain, otherwise known as serial kinematic manipulators (SKM), are highly articulated and flexible; however have the drawback of limited accuracy due to the compounding of errors through each joint. Serial kinematic manipulator forms include Cartesian, cylindrical, spherical, SCARA as well as fully articulated configurations. (Yeshmukhametov et al., 2017)

Conversely, a closed kinematic chain, or parallel kinematic manipulator (PKM), is considered to be rigid, accurate, and have high theoretical dynamic potential; however have a limited working envelope due to the configurations inherent lack of flexibility.

PKM architectures come in a huge variety of geometries. The geometry and symmetries experienced in the different architectures dictate the

[a] https://orcid.org/0000-0003-1102-8255
[b] https://orcid.org/0000-0003-0358-5289

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overall singularities, which affect the kinematic equations and control of the mechanism. These differences allow for great research potential. (Yeshmukhametov et al., 2017) (Pandilov and Dukovski, 2012) (Carricato and Parenti-Castelli, 2002)

A combination of closed and open chains into one configuration may be considered a hybrid kinematic manipulator (HKM). Ideally, a hybrid mechanism should have the advantages of both the SKM and PKM's.

There are currently several variants hybrid kinematic mechanisms being researched, however the majority are of a closed chain configuration. One hybrid mechanism that has been introduced widely into industry is that of the palletizing robot. Palletizing robots are used extensively for handling, moving, loading, stacking and alike of large geometry and weight items in industrial applications. These tasks would otherwise be unsuitable for a human to perform repeatedly. (Tao et al., 2014)

Although used extensively in industry, there is minimal literature surrounding the theory and kinematic modelling of these quasi-serial palletizing manipulators. The novelty of this research paper looks to outline some of the fundamental theory and the initial stages of the kinematic model. The research also outlines rapid prototyping for testing purposes, as well as the derivation and validation of the kinematic equations of a quasi-serial manipulator.

2 QUASI-SERIAL

A palletizing robot, illustrated in Figure 2, as mentioned, is a hybrid mechanism, specifically a quasi-serial mechanism.

A quasi-serial manipulator is an open kinematic chain, similar to a SKM, however has one or more closed kinematic loops within its structure, similar to a PKM. These closed loop kinematic parallelograms allow for increased dynamic potential; however, each closed loop parallelogram will reduce the overall Degrees of Freedom (DOF). (Shaik et al., 2012) (Sun and Fang, 2018) (Issa et al., 2017)

A quasi-serial manipulator is able to achieve greater dynamic potential when compared to a standard open chain serial manipulator, due to the relocation of mass lower down, hence decreasing inertial effects as well as non-linearity's within the architecture. A quasi-serial manipulator therefore is more agile than a PKM and has the ability to carry greater loads compared to a SKM. The overall footprint of the quasi-serial mechanism is compact such like a SKM. (Klimchik et al., 2016) (Klimchik and Pashkevich, 2017)

Figure 2: Industrial palletizing robots. (Klimchik and Pashkevich, 2017).

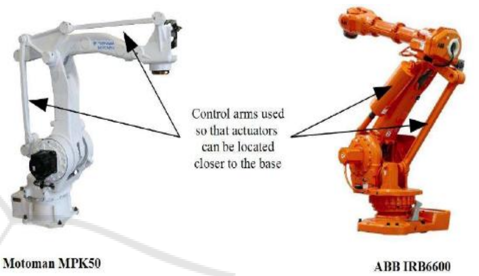


Figure 3: Different quasi-serial manipulators. (Shaik et al., 2012).

Illustrated in Figure 3 are two quasi-serial open chain manipulators; both containing closed loop parallelograms, and lowered centre of gravity. All of the actuation motors are situated co-linear at the base of the manipulator, allowing movement of the end effector through a combination of active and passive joints, similar to that of a closed chain PKM, or four-bar mechanism.

3 RAPID PROTOTYPING

In order to perform further research and testing, a physical model was required. Due to the high cost involved in designing and optimising via several iterations, it was decided to rapid prototype an existing quasi-serial architecture.

A design by Florin Tobler named 'RobotArm', which is accessible at Thingyverse.com under the Creative Commons Licence, was proposed. The design is that of a three DOF quasi-serial mechanism, illustrated in Figure 4. (Tobler, 2016)

Rapid prototyping, otherwise known as 3D printing, was utilised in order to produce the mechanical components of the RobotArm design. Rapid prototyping or 3D printing is a new technology based

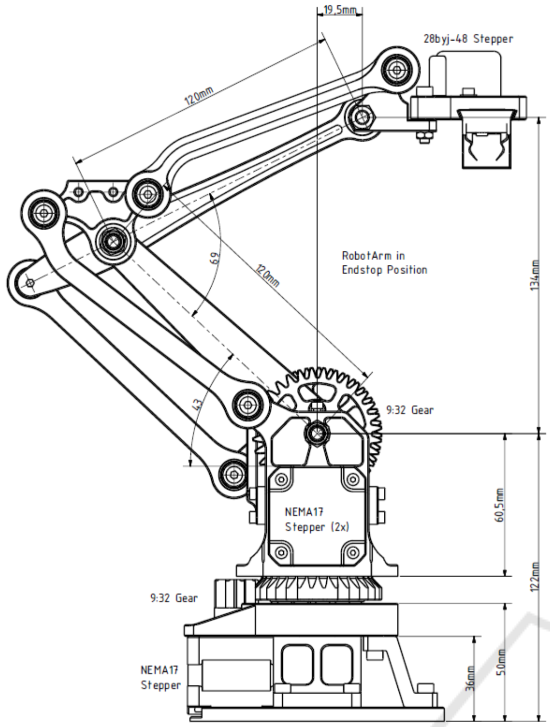


Figure 4: RobotArm by Florin Tobler. (Tobler, 2016).

on additive manufacturing. When compared to traditional subtractive manufacturing, 3D printing is much leaner on raw materials. Complex geometries can be achieved through the additive manufacturing process.

The parameters outlined in Table 1 were input into Cura version 3.5.1 which was used to slice the model, thus creating a G-code required to 3D print the mechanical components.

Table 1: 3D printing parameters.

PARAMETER	QUANTITY
Material	PLA+
Tensile breaking strength	57.8 MPa
Modulus of elasticity in flexure	2.3 GPa
Density	1.23-1.25 g/cm3
Layer Height	0.16 mm
Shells	4
Infill	Rectilinear
Infill %	60
Nozzle Temp	215 °C
Bed Temp	55 °C
Print Speed	50 mm/s

As a result, the following components were printed with approximately 0.2mm tolerance on the overall dimensional accuracy. This tolerance is due to the shrinkage of the plastic after cooling.

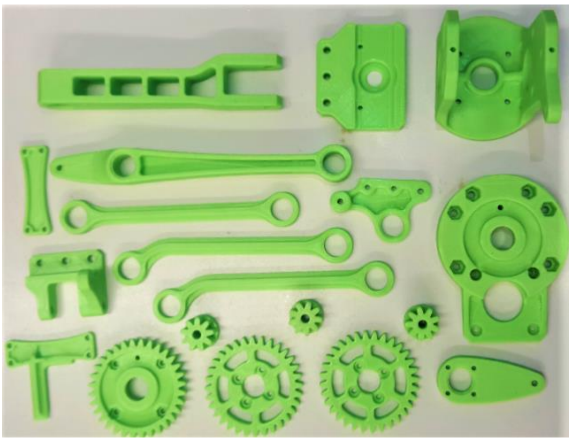


Figure 5: 3D printed components of RobotArm.

The assembly of the RobotArm required a number of bearings, nuts, bolts and electronic components.

The hardware utilized for the RobotArm are as follows:

- 3 x NEMA 17 Stepper Motors
- 1 x Servo Motor – end effectors gripper
- 1 x Arduino Mega 2560 Microcontroller
- 1 x RAMPS 1.4 Shield
- 3 x A4988 Stepper Motor Drivers
- 3 x Mechanical Limit Switches

The mechanical limit switches were not part of the original design, however, have been introduced in order to perform a homing sequence. Homing is required for all CNC machines in order to outline the working envelope and define a reference point.

This combination of hardware is almost identical to that of a traditional RepRap 3D printer; hence, Arduino software will be the base of the control system.

4 KINEMATICS

Equations that relate geometric properties and joint positions needed to be derived in order to define the end effectors position in 3D space. Figure 6 illustrates the physical dimensions and relative joint positions of the quasi-serial manipulator being researched.

The design of a quasi-serial manipulator consists of two co-linear actuation joints, namely OA and OC. The End Effector (point EE) is connected to the Origin (point O) via three closed loop parallelograms. The assignment of joint frames, according the Denavit-Hartenberg method, becomes difficult and hence a different approach was selected to solve the kinematic equations.

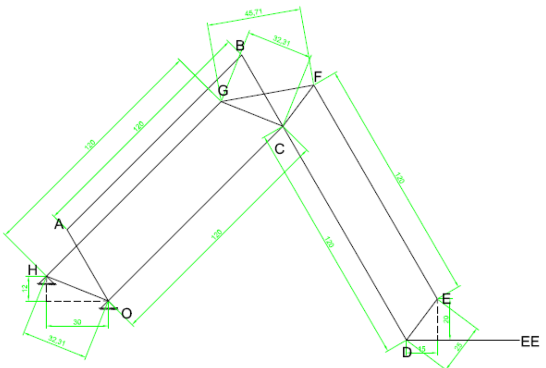


Figure 6: RobotArm dimensions.

A closed loop vector can be set up between point O and point D, on the EE. This vector loop between points OCD is illustrated in Figure 7. (Liu et al., 2019) The closed loop vector equation is therefore:

$$\vec{r} = \vec{a} + \vec{b} \quad *(1)$$

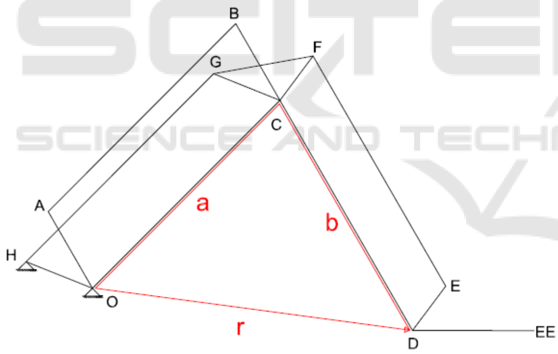


Figure 7: Vector loop.

Where $\vec{a}$ is the vector along OC, and $\vec{b}$ is the vector along CD. (Liu et al., 2019)

In order to solve vector $\vec{a}$ and $\vec{b}$ many of the internal angles needed to be defined. These angles are defined symbolically in Figure 8.

Hence:

$$\vec{r} = \overrightarrow{OZ} + \overrightarrow{ZD} \quad (2)$$

$$\overrightarrow{OZ} = L_1 \cos\theta_1 \quad *(3)$$

$$\overrightarrow{CZ} = L_1 \sin\theta_1 = L_6 \sin\beta \quad (4)$$

$$\overrightarrow{ZD} = L_6 \cos\beta = L_6 \sin\emptyset \quad *(5)$$

$$\alpha = \theta_2 - \theta_1 \quad (6)$$

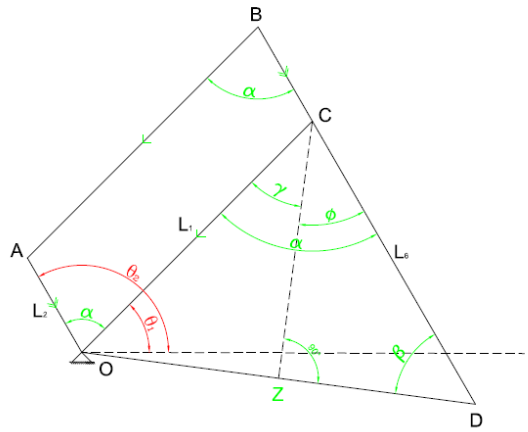


Figure 8: Vector triangle with angles.

$$\alpha = \gamma + \emptyset = (0.5\pi - \theta_1) + \emptyset \quad (7)$$

$$\therefore \theta_2 - \theta_1 = (0.5\pi - \theta_1) + \emptyset \quad (8)$$

$$\therefore \emptyset = \theta_2 - 0.5\pi \quad *(9)$$

$$\theta_1 + \alpha + \beta = \pi \quad (10)$$

$$\theta_1 + (\theta_2 - \theta_1) + \beta = \pi \quad (11)$$

$$\therefore \beta = \pi - \theta_2 \quad *(12)$$

$$\vec{r} = \begin{cases} x = L_1 \cos\theta_1 + L_6 \cos\beta \\ y = L_1 \sin\theta_1 - L_6 \sin\beta \end{cases} \quad (13)$$

$$\therefore \vec{r} = \begin{cases} x = 0.12 \cos\theta_1 + 0.12 \cos(\pi - \theta_2) \\ y = 0.12 \sin\theta_1 - 0.12 \sin(\pi - \theta_2) \end{cases} \quad *(14)$$

This set of equations define the end-effectors position in 2D planar space, according to two inputs, namely theta-one (θ_1) and theta-two (θ_2). Where θ_1 is the angle between the x-axis and limb OC, and θ_2 is the angle between the x-axis and OA.

Due to the inherent design of the quasi-serial manipulator, the end-effector does not change rotational orientation for any Cartesian coordinate, henceforth remaining perpendicular to the x-axis. (Liu et al., 2015)

Using the same graphical approach, the inverse kinematic equations can be derived.

5 TESTING

To ensure that the derived forward kinematic equations, outlined in Section 4, were defining the end-effectors position correctly in 2D planar space; tests between the physical model and the kinematic equations needed to be performed. Initially a graphical test approach was adopted, and subsequently an analytical approach. The results of each test sample can then be compared for offset error. In order to achieve sound experimental data, it was vital to produce several accurate graphical representations of the quasi-serial manipulator in different poses and end-effector positions. Therefore, the links were modelled on SolidWorks in accordance with the provided geometries of the RobotArm. The links were then mated with the introduction of mate joint limits. The mate limits are in accordance with the physical and geometrical limits of the RobotArm. Making θ_1 (actuates link OC) and θ_2 (actuates link OA) random angles within the mate limit controller, and subsequently measuring from point O to point D, SolidWorks provides a value for dX and dY. This empirical x and y value can then be compared to an analytical result.

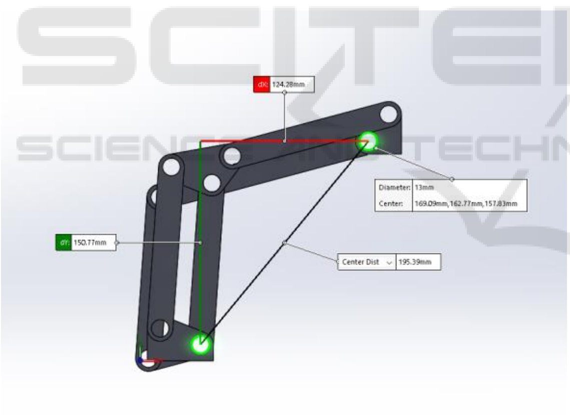
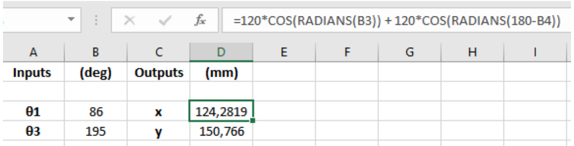


Figure 9: Graphical testing via SolidWorks.

Figure 9 illustrates the graphical result for an input of $\theta_1 = 86°$ and $\theta_2 = 195°$.
In order to produce several analytical results accurately, an Excel spreadsheet was set up with two inputs and two outputs linked through the kinematic equations from Equation 14. It was necessary to convert the input angles from degrees into radians for the Excel calculation. The output is an x and y coordinate value of point D, comparable to the results from the graphical approach.
Figure 10 is a snapshot of the Excel spreadsheet used. It illustrates the results of the derived kinematic equations from the same inputs as Figure 9.


=120*COS(RADIANS(B3)) + 120*COS(RADIANS(180-B4))

A	B	C	D	E	F	G	H	I
Inputs	(deg)	Outputs	(mm)					
θ1	86	x	124,2819					
θ3	195	y	150,766					

Figure 10: Analytical testing via Excel spreadsheet.

This procedure was repeated for several different θ_1 and θ_2 inputs. The results of both the empirical and analytical tests, for each different end effectors positions, are represented in Table 2 for comparison.
It can be seen from Table 2 that the results correlate extremely closely, with less than 0.1% difference between the measured empirical position and the calculated analytical position. This result implies that the forward kinematic equations derived in Section 4 are accurately describing the end-effectors position in 2D planar space.

Table 1: Empirical vs analytical results.

Inputs (degrees)		**Empirical (mm)**		**Analytical (mm)**		**Error (%)**
θ_1	θ_2	**x**	**y**	**x**	**y**	
86	195	124.28	150.77	124.3	150.8	-0.018
74.5	175.5	151.7	106.22	151.7	106.2	0.006
64	152	158.56	51.52	158.6	51.5	-0.019
43	125	156.59	-16.46	156.6	-16.5	-0.004
22	103	138.26	-71.97	138.3	-71.9	-0.076
10	70	77.13	-91.93	77.1	-91.9	0.035

6 CONCLUSIONS

The paper described the major classifications of current industrial robots, namely serial and parallel mechanisms, ie SKM and PKM. The concept of a hybrid robot was then introduced with the hypothesis that a hybrid mechanism would have the advantages of both the serial and the parallel architectures. Theory and current examples of hybrid mechanisms were outlined briefly followed by the concept of a hybrid open chain manipulator, or quasi-serial manipulator. Quasi-serial manipulators have begun to be prominent for material handling operations.
The selection of a current quasi-serial manipulator was made in order to perform further research and

validation. This quasi-serial RobotArm desktop model was subsequently rapid prototyped via 3D printing. The parameters input into Cura for slicing of the model have been outlined in Section 3.

The kinematic model was then derived for 2D planar space via a closed loop vector method. These kinematic equations needed to be validated and hence an empirical versus analytical test approach was implemented. The graphical empirical results were obtained with the use of an equivalent SolidWorks model of the physical RobotArm geometry. The analytical results were obtained via the forward kinematic equations outlined in Section 4. The results were then tabulated in Section 5 and subsequently compared. The results correlated extremely closely well with a maximum error of less than 0.02%.

Future work looks to define the inverse kinematic equations, develop a 3D workspace for a single RobotArm, including singularities and non-linearities. Further is to then introduce several of these RobotArms into the same workspace for collaborative applications. A Graphical User Interface (GUI) will be developed in order to control and monitor the final platform.

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