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Review Article

A Comprehensive Review Based on Analysis Modeling, Mechanical Vibration Control Strategies, and Optimization Methods of Robotics Flexible Manipulator Structures

Abbas Moloody[1], Azizan As'arry[1]*, Tang Saihong[1], Raja Kamil[2] and Mohd Zuhri Mohamed Yusoff[1,3]

[1]Advanced Engineering Materials and Composites Research Centre (AEMC), Department of Mechanical and Manufacturing Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM, Serdang, Selangor, Malaysia

[2]Department of Electrical and Electronics Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM, Serdang, Selangor, Malaysia

[3]Laboratory of Biocomposite Technology, Institute of Tropical Forestry and Forest Product (INTROP), Universiti Putra Malaysia, Serdang 43400, Selangor, Malaysia

ABSTRACT

Flexible Manipulators (FMs) provide a number of benefits, containing reduced weight due to the thinness of the robot's linkages. Although the initial plan was to use actual robots' flexibility or slenderness to their advantage, the complex dynamics of the systems piqued interest in using an experimental flexible manipulator as a testing ground for various modeling or control strategies. A review is essential for researchers who want to align their study objectives with those of the field because the literature is extensive and diverse. Due to the widespread usage of flexible manipulators in different mechatronic and robotic applications over the past few decades, many academics worldwide are now interested in researching this topic. Studies are categorized here according to the control and modeling technologies of flexible manipulators and methodologies. Review of recent works on analysis, modeling, mechanical vibration, control algorithms, gyroscope technology and applications, difficulties in managing flexible manipulators and their anticipated future, and the majority of the notable evolutionary and optimization algorithms, including Genetic Algorithm (GA), Differential Evolution (DE), and Fuzzy Logic (FL), as well as modification approaches and techniques, are discussed and underlined. This study examines many publications, thoroughly reviewing the analytical, mathematical, dynamical modeling,

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E-mail addresses:
a.moloody@yahoo.com (Abbas Moloody)
zizan@upm.edu.my (Azizan As'arry)
saihong@upm.edu.my (Tang Saihong)
kamil@upm.edu.my (Raja Kamil)
zuhri@upm.edu.my (Zuhri Yusoff)
* Corresponding author

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mechanical vibration control techniques and most of the notable evolutionary and optimization algorithmic approaches of Robotic Flexible Manipulator (RFM) structures.

Keywords: Differential evolution, double links, mechanical vibrations, multi-links, optimization, robotics flexible manipulator, single link

INTRODUCTION

Mechatronics and robotics areas and systems have garnered increasing interest from researchers in recent years because of their widespread usage in engineering science and scientific research applications, such as space exploration, undersea surveys, industrial and military sectors, welding, painting, assembling, and medical applications. Robotic and mechatronic manipulators are multi-segment devices that are electronically controlled and interact with their surroundings to carry out tasks. As shown in Figure 1, every component of mechatronic systems requires research and development (R&D) work. These manipulators are widely used in industrial production and have many other specialized applications. Generally, these manipulators are divided into Rigid Manipulators (RM) and Flexible Manipulators (FM). Much research has been done to design methods for modeling and controlling flexible robotic control systems. Therefore, various experimental investigations were performed to verify the proposed modeling and control methods. Dynamic and mathematical modeling, analysis, and control of dynamic mechanisms began in earnest in the 1970s. Pole Position (PP) (Paul et al., 1988), Lyapunov-Based Control (LBC) (Ge et al., 1996), and Integrated Resonance Control (IRC) (Pereira et al., 2011) are just some of the feedback control methods that have been studied for precise positioning and vibration control of single-link robotic flexible manipulators. This discussion presents an overview of the foundation, control and modeling of robot flexible manipulators and the popular theory of evolutionary algorithms that have been extensively studied to address the areas of optimization and applications and different techniques since its introduction by Storn and Price (1997).

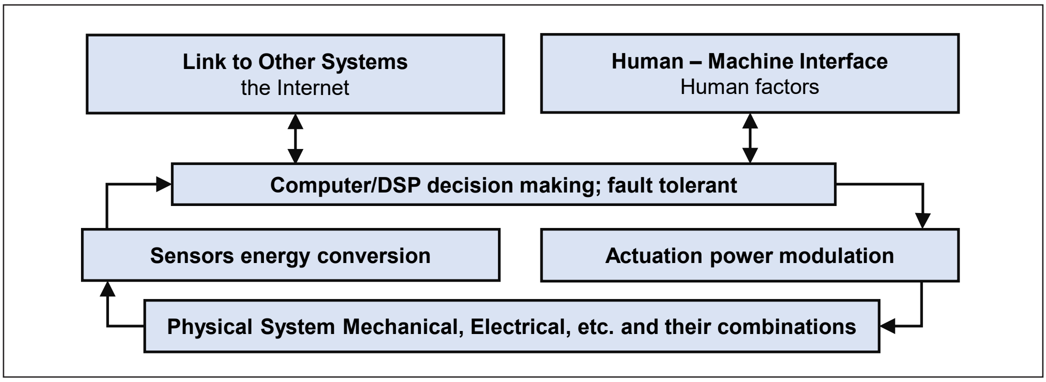
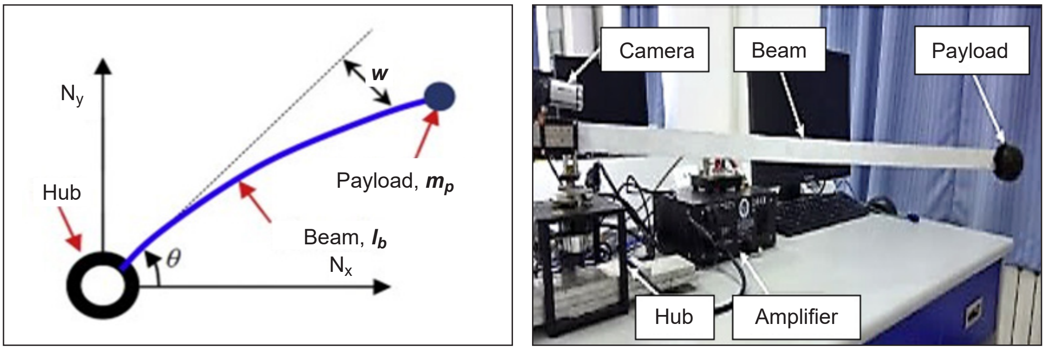


Figure 1. Typical of a mechatronic system block diagram

MATERIALS AND METHODS

Robotics Flexible Manipulator (RFM) Structures

Robotic Flexible Manipulators (RFM) are typically employed to pick up loads and transport them to a predetermined place. It has a number of benefits over Rigid Robotic Manipulators (RRM), including quick reaction, reduced power consumption, less weight, a smaller actuator required, a cheaper total cost, more maneuverability, and ease of transport. An example of a typical RFM for a single connection is shown in Figure 2. However, because of the complexity of multi-link systems, experimental development is restricted to single-link manipulators. Flexible manipulators are an essential advancement in robotic systems, aiming to increase productivity. They are suitable for a wide variety of jobs and environments. They are in high demand to replace humans in difficult jobs, routine tasks, and dangerous situations to perform operations faster, more profitably, and more precisely. Therefore, RFM dynamic analysis and controller design are more difficult to solve. Despite its advantages, the main disadvantage of RFM is vibration failure due to its low stiffness (Chen et al., 2019).



(a) (b)

Figure 2. Configurations of a typical RFM : (a) Theoretical model; and (b) Experimental model (Chen et al., 2019)

Mechanical Vibration of (RFM) Structures and Suppression

For many years, attempts have been made to preserve mechanical vibration factors and regulate mechanical vibration. Vibration reduction methods are divided into passive and active approaches (Figure 3) (Vishal & Aradhye, 2016). Vibration causes are protected by eliminating extra energy sources, reducing input forces, and isolating them from external disturbances. The parametric adjustments mostly affect the mass and stiffness of parts. Vibrations are an unwelcome occurrence in construction. Structures may be damaged, or system performance may be harmed as a result of the unwanted vibration. Vibration reduction is a serious concern when using flexible structures, especially in the aircraft and

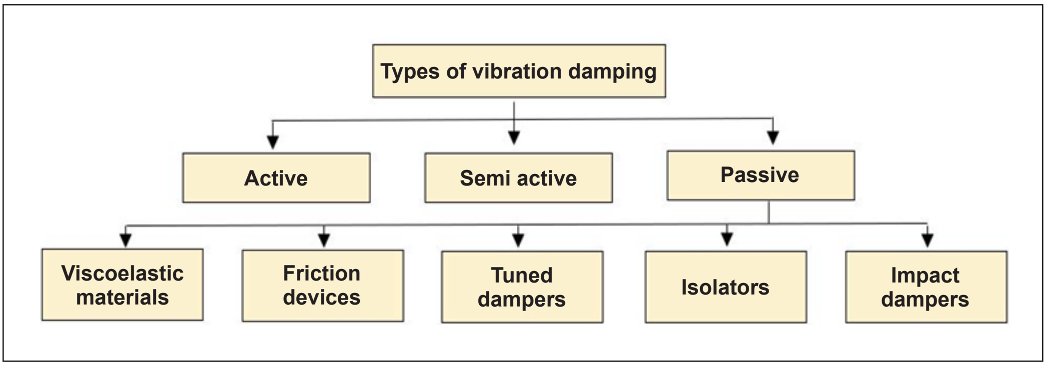
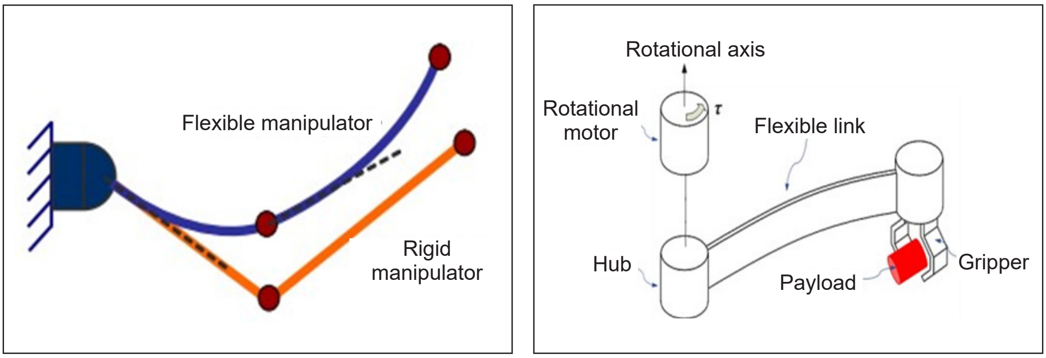


Figure 3. Flow chart for types of vibration damping (Vishal & Aradhye, 2016)

robotics sectors. However, controlling, reducing, and suppressing RFM vibrations are still regarded as major and critical issues.

Modeling Strategies of RFM Structures

The dynamic model is the foundation for dynamic analysis, dynamic performance evaluation, and manipulator optimization design when modeling and analyzing flexible manipulators. In investigating such systems' dynamic behavior and control, the many applications of flexible manipulators draw much interest. However, because of the lengthy and connected set of dynamic equations and the system's flexibility, this is recognized to be a challenging task (Rahimi & Nazemizadeh, 2014). Figure 4 shows that such systems have no exact solutions. Figure 4(b) depicts the design of a robot single-link flexible manipulator with a clamp. By analyzing integrated mode (Tang et al., 2021), three types of single-link RFMs have been studied: single-link flexible manipulators, single-link rigid-joint manipulators, and single-link rigid-joint manipulators.



(a) (b)

Figure 4. (a) Configurations of Flexible Manipulator (FM) and Rigid Manipulator (RM) (Rahimi & Nazemizadeh, 2014); and (b) Configurations of Flexible Manipulator (FM) (Tang et al., 2021)

Modeling of Single-link RFMs

The discussion is on the flexible single-link manipulator modeling literature and groups contributions into categories, models, and additional investigations. However, the robot model must include the system's non-linear dynamics and dynamic parameters for flexible robotics analysis. The four basic finite-dimensional models, such as the Lumped Parameter (LP) (Huston, 1980), Assumed Modes (AM) (Alandoli et al., 2016), Finite Elements (FE) (Lochan et al., 2016), and Concentrated Mass (CM) models (Pereira et al., 2014), are generally used to represent the dynamic equations of these systems.

Modeling of Double Links RFMs

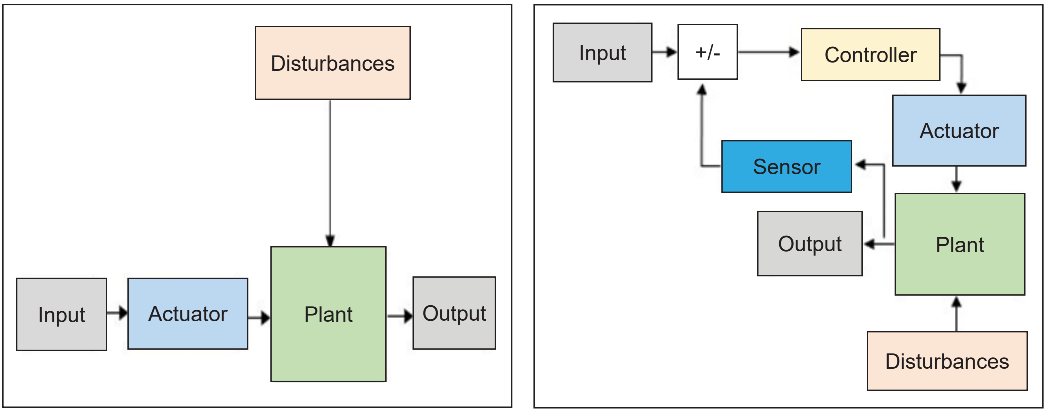
Robotic manipulators with a few flexible links are desirable because they do not suffer from the significant control issues brought on by the heavy inertia forces produced when the rigid, heavy links in traditional robots move at high speeds. In reality, only two of the average six-link industrial robot's links frequently experience large inertial forces, so these two links should be flexible. Planar dynamic model developed by Vakil adaptable link by integrating the Assumed Mode Method (AMM) with Lagrange's Equation and taking into consideration the tip mass and mass moment of inertia, flexible joint Manipulators of two links, or double manipulators, were created (Vakil et al., 2012).

Modeling of Multi-RFMs

Jian and Wen (2017) demonstrate the bias of an n-linked robot's flexible manipulators using finite terms of series and the Euler-Bernoulli beam model. The Lagrangian method is applied to the dynamics system to obtain the dynamics equation of the general soft manipulators of the n-linked robot. Contrary to single-link manipulators, multi-link RFMs cannot be calculated using a linearized model, as realized by Cannon and Schmitz (1984).

Classical Control Strategies of RFM Structures

There are two basic types of control techniques for RFM systems: feedforward (Open Loop) (OL) and feed-back (Closed Loop) (CL). While feedback control techniques employ estimation and measurement of the system states for controlling the rigid body motion and vibration suppression, feedforward approaches are mostly designed for vibration suppression and include changing the input command or reference to minimize system vibrations. The control of RFMs is covered in this part, along with evaluations of feedforward and feedback control methods (Cannon & Schmitz, 1984) (Figure 5).



(a) (b)

Figure 5. (a) Open loop and; (b) Closed loop control system (Cannon & Schmitz, 1984)

PID Control Techniques of RFMs

Proportional, Integral, and Derivative (PID) control is a relatively simple closed-loop system. The signal driving the plant consists of a proportional gain (K_P), an integral gain (K_I), and a derivative gain (K_D). Thus, PID was coined in Equation 1 and Figure 6. On the error signal, the proportional gain is a pure gain adjustment.

$$u(t) = [K_P\, e(t) + K_I \int_0^{\tau} e(t)dt + K_D \frac{de(t)}{dt} = K_p + \frac{1}{s}\, K_I + K_D S] \qquad [1]$$

The error signal is the discrepancy between the plant's location and the targeted position. The derivative gain modifies the plant's damping, whereas the integral gain modifies the plant's accuracy (Bansal et al., 2017).

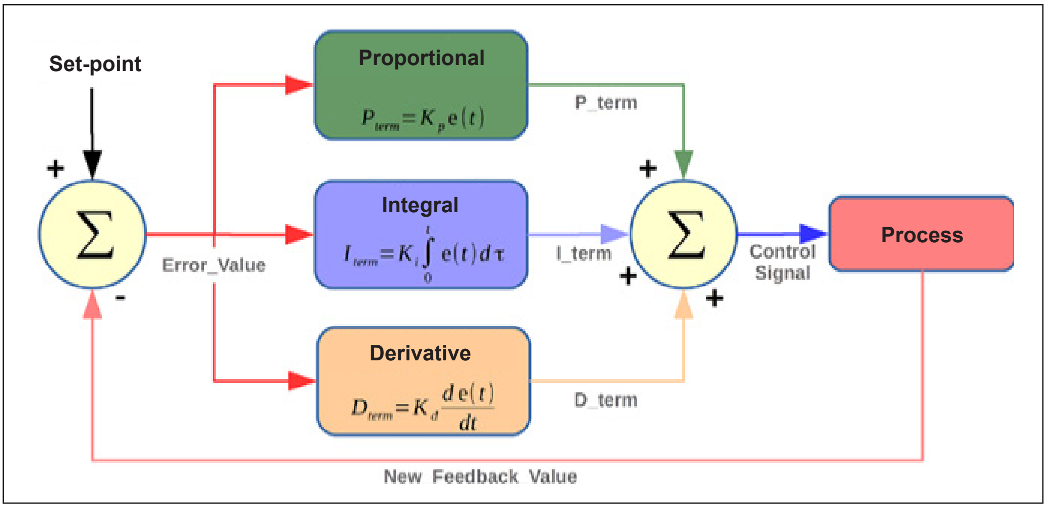


Figure 6. PID control scheme (Bansal et al., 2017)

Intelligent Control Strategies of RFM Structures

Intelligent control based on Fuzzy Logic (FL) (Mbede et al., 2003), Figure 7 Neural Networks (NN), (Rahimi & Nazemizadeh, 2014), Figure 8 and Genetic Algorithms (GA) is a method that appears promising for the control of RFM systems. Intelligent control systems have been designed in great detail for many control applications. Previous studies have demonstrated that intelligent control methods perform better than alternative control strategies for some systems. For flexible manipulators, NN-based controllers have been developed and put into use after much work. Learning control, as it was first termed, was first investigated in the 1960s (Tsypkin, 1968). Since then, its popularity and range of applications have steadily risen, and it is being used in practically all fields of science and technology.

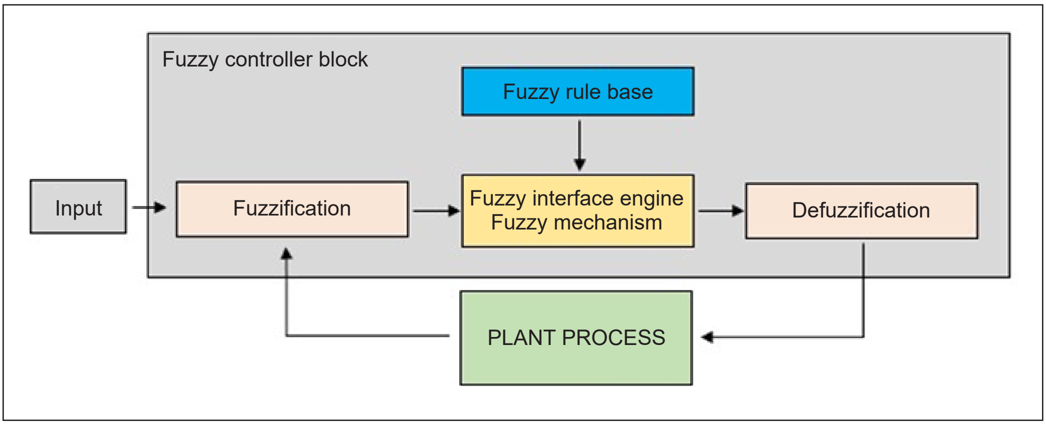


Figure 7. Block diagram of fuzzy logic control system (Mbede et al., 2003)

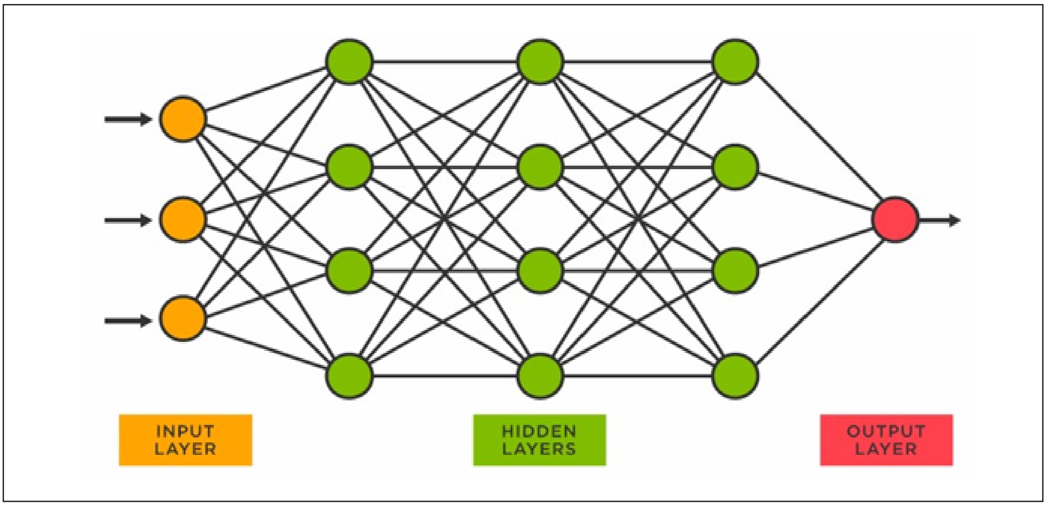


Figure 8. Structure of artificial neural network system (Rahimi & Nazemizadeh, 2014)

Combined Control Strategies of RFM Structures

Active Force Control of RFMs

Robots often interact with objects found in the workplace as part of various manipulation tasks. Controlling the forces the manipulator produces in its surroundings is preferable rather than only the end effector's position. Small changes in the end effector's trajectory for a rigid manipulator can produce extremely high contact pressures that might be detrimental to the objects, the robot and the people it interacts with (Spong & Vidyasagar, 1989). AFC, in general, is a mathematical framework for identifying torque or force disturbances in a system and makes calculations easier by anticipating compensating torque. Active Force Control (AFC) and intelligent calculations have long been coupled for superior results. This combination has been applied in a variety of circumstances. Fuzzy logic, Genetic Algorithms (GA), Neural Networks, and iterative learning are used for effective integration. The purposeful application of force to offset external vibration effects is known as Active Vibration Control (AVC). Active vibration control systems have become a feasible option for bridging the low-frequency gap, as shown in Figure 9.

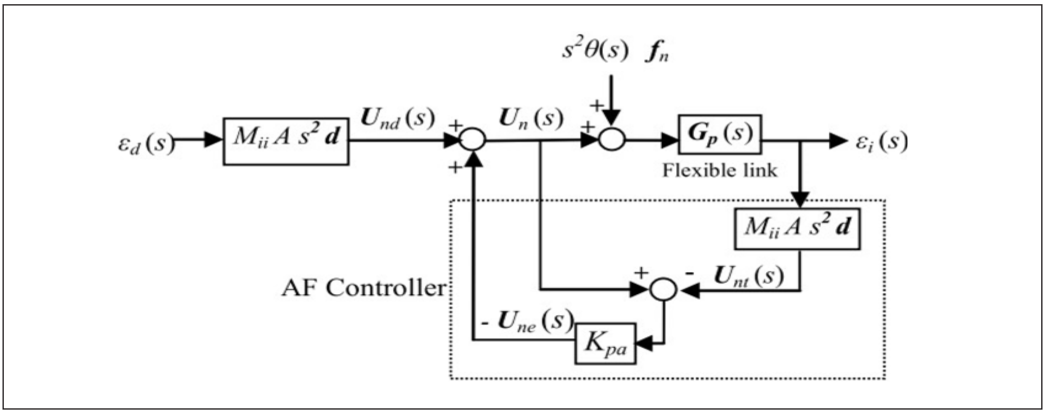


Figure 9. AF controls the flexible manipulator block diagram (Abdul et al., 2014)

Active Vibration Control of RFMs

According to recent papers, active Vibration Control (AVC) is increasingly used with new hardware technologies. Piezoelectric actuators and sensors are among the new available sensors and actuators. AVC reduces the amplitude of vibration in dynamic systems. It works by synthesizing the cancellation signal and absorbing unwanted disturbance forces to artificially reduce the impact of vibration on the system. For managing and reducing FLM vibration, (Kiang et al., 2015) outlined the benefits and drawbacks of various control strategies used for AVC in FLMs, which are depicted diametrically opposite in Figure 10. The installation of piezoelectric material along the link improves the detection and control capacities of the vibration-suppression system by serving as both an actuator and sensor (Figure 11) (Bailey et al., 1985).

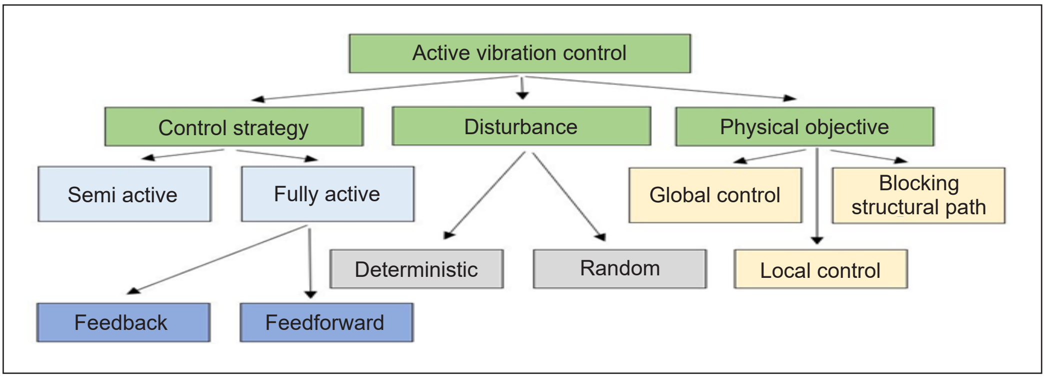
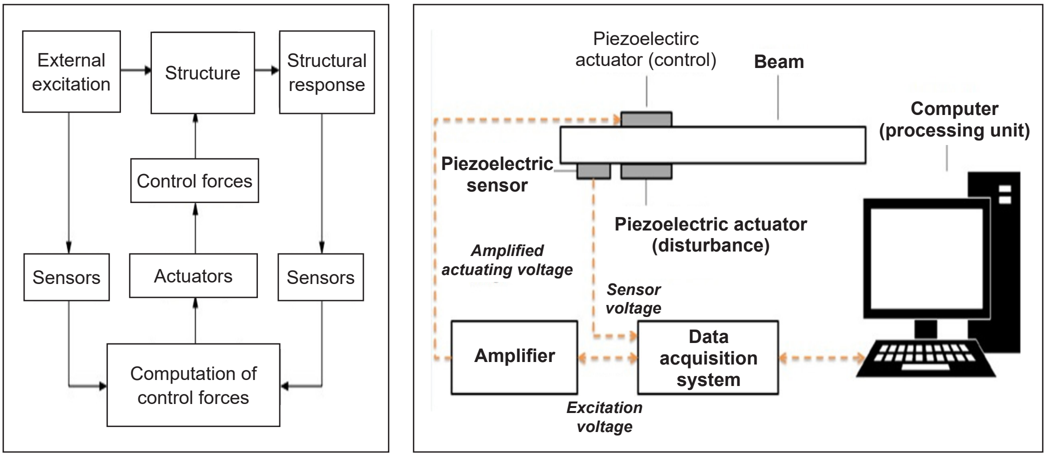


Figure 10. Control schemes (Kiang et al., 2015)



(a) (b)

Figure 11. (a) The general idea of the AVC damping system; and (b) modeling and AVC of a flexible beam (Ros et al., 2015)

Semi-active and Passive Vibration Control of RFMs

Depending on the dynamic reaction, the semi-active system uses a variable stiffness or variable damping mechanism to change the structural properties of structures. In a semi-active system, control devices and indirectly acting forces that affect objects are powered by limited power sources. Semi-active control systems can dynamically change their attributes without adding energy to the building. Magnetorheological (MR) dampers, variable orifice dampers, and tunable liquid dampers are examples of semi-active devices. They use a variety of passive damping strategies, including viscoelastic materials, friction devices, tuned dampers, isolators, and impact dampers.

Velocity Feed-back Repetitive Control of RFMs

Green and Sasiadek (2002) employ repeated control and fuzzy logic, with the primary objectives being to reject periodic disturbances (including in the steady state) and follow periodic references with zero steady-state error. Until the effects of flexibility are removed, the controller iteratively repeats the recurrent trajectory control to control a two-link RFM. Feliu et al. (2005) developed a repetitive control-based control scheme for single-link RFMs. However, it suppresses vibrations upon execution of each motion to avoid the need for recursively repeated trajectories.

End-point Acceleration Feedback Control of RFMs

Although it is no longer as tempting for research involving robots, this control approach has been the focus of various study inquiries during the past 20 years (Paul et al., 1988). Based on end-point acceleration sensors, they developed a proportional feedback control system for a cantilever beam with a bonded piezoelectric patch actuator. An acceleration feedback controller was created using the forced vibration of an intelligent cantilever beam. The design accounts for external harmonic disruption (An et al., 2013).

Control Issues and Difficulties of RFM Structures

The elastic deformation and associated oscillation at the tip cause FLMs to lose stability. Flexural vibrations at the ends of the links are undesirable during movement since the flexible link itself may have several degrees of freedom (Pradhan & Subudhi, 2012). These challenges are exacerbated when traveling at high speeds because these FLMs display non-minimum phase (i.e., unstable zero dynamics) (Rokui & Khorasani, 2000) characteristics and have exceedingly intricate and non-linear dynamics. These systems introduce undershoots, a time-delay phenomenon (Yurkevich, 2011). The FLM's highly non-linear governing equations may have unlimited freedom depending on the manipulator geometry.

Future Vision of RFM Structures

Flexible robotics is an area of autonomous systems that has received much research due to the vast quantity of material written on the subject over the past thirty years. Even entire books have previously been written on it (Tokhi & Azad, 2008). The physical platform's simplicity allows for the study of novel control strategies. However, as Benosman and Vey (2004) stated, most modeling and controllability-related subjects have already been properly covered in earlier work. Some issues, however, remain unresolved and provide room for significant advancement. Certain manipulators with a tiny stiff arm joined to a big flexible base have been created for precise jobs. However, the problem of creating flexible robots with features resembling real industrial robots has not yet been fully resolved. Applications for robots doing grabbing, polishing, surface identification, and shape identification, among other activities, can be created (Somolinos et al., 2002).

Sensors and Actuators of RFM Structures

Open-loop (feedback control) or closed-loop (feedback control) strategies can modify the FLM tip's trajectory. The two types of feedback controllers are collocated control and non-collocated control. These include robust control (based on linear state feedback), adaptive control, robust control (based on robust control), and robust control (based on robust control). Intelligent control is based on neural networks or fuzzy logic. The tip displacement, via the strain or acceleration of the manipulator, accounts for most feedback signals for FLMs (Feliu et al., 2005) (Figure 12).

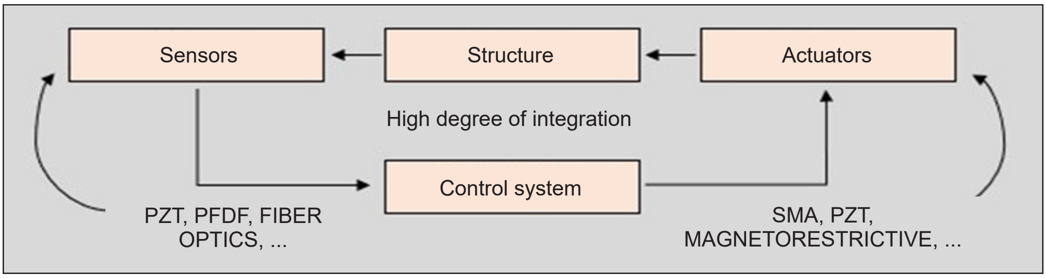


Figure 12. Smart structure, (Dubravko, 2009)

Accelerometer

Accelerometers employed an accelerometer to confirm that the combined strain gauge and camera outputs were accurate. A piezoelectric acceleration sensor was fastened to a link at a certain location (Paul et al., 1988) and utilized as feedback for the positive position feedback control technique. According to Li et al. (2013), an accelerometer measured the end-point position and transmitted it to the motor controller for a flexible manipulator system's combined feedforward and feedback control.

Ultrasonic Sensor

A single-link RFM uses an ultrasonic sensor positioned at the tip and a receiver fastened at the hub to detect the link's deflection (Ho & Tu, 2006).

Position Sensitive Devices

A Position Sensitive Device (PSD) was attached to the tip of a single-link RFM to measure tip deflection, and the PSD and an accelerometer were attached to the tip of a single-link RFM to estimate tip deflection and tip velocity. This technique was used in Mahmood et al. (2007).

Piezoelectric Materials

As the use of lead zirconate titanate (PZT), Piezoelectric materials are frequently employed as sensors and actuators in smart constructions because of this coupling property. Piezoelectric patches were used to measure vibration in a flexible link composite manipulator. PZT was employed as an actuator to regulate the vibration of the cantilever beam (Dong et al., 2006).

Gyroscope Technology and Applications

Gyroscopes (G) challenge underactuated systems, often employed as actuators in various plants, such as unground haptic devices, satellites, and undersea vehicles. Gyroscope control design has been the subject of several publications (Rodr´ıguez et al., 2017). The external torques that affect those systems are unknown disturbances. The gyroscope's Rigidity (R) and Precession (P) qualities have been used in engineering design for a long time. Gyroscopes must be rigid to keep their orientation in space while spinning. When a frame is spinning, a gyroscope installed on the frame can be used to measure or maintain orientation and angular velocity. It is a wheel supported by two or three gimbals, which are pivoting supports that enable the wheel to rotate around a single axis. John Serson invented the first thing that resembled a gyroscope in 1743 (Braghin et al., 2007).

Optimization Methods of RFM Structures

Flexible structures have been utilized with effective vibration control methods and approaches, such as Differential Evolution Optimization (DEO), to achieve the required vibration suppression for precise accuracy. Different controller settings can be tuned to improve different control system characteristics depending on the system's kind and performance. The error signal, its derivatives, and occasionally its integral, as well as other state variables and auxiliary variables employed as input signals, are all given to the controller in such a system (Jung et al., 2015).

Evolutionary Algorithm Modification Method

Metaheuristic Search Algorithms (MSAs) are envisioned as suitable options to meet complex modern optimization difficulties by employing their search procedures influenced by numerous natural phenomena. Differential Evolution (DE), an MSA created by Storn and Price (1997), is regarded as one of the most widely used optimizers to address challenging optimization issues. DE, a population-based approach from the Evolution Algorithms (EA) family, is frequently used for diverse optimization issues. It produces new offspring under certain conditions by recombining solutions, in contrast to other Evolution Algorithms (EAs), employing scaled difference vectors to disturb the solutions and create offspring. If the new child solution outperforms the old individual solution, the old individual solution will be removed. Many academics focus on improving the efficiency of the DE algorithms, with each group of researchers focusing on one of the DE stages or components. Xiang et al. (2015) presented a novel DE mutation method that combines the DE/current/1/bin and DE/pbest/1/bin mutation techniques.

Genetic Algorithm Method

Genetic algorithm control (GA) is a technique for intelligent control that is not model-based. It uses a search technique based on how natural selection functions. A stochastic search algorithm belongs to the class of heuristic approaches. GA mimics the genetic processes of natural evolution to resolve optimization problems. Online and offline applications of GA methods are possible. GA is paired with other traditional and reliable controls for several TLFM control characteristics. Research methods based on natural selection and genetics are known as genetic algorithms (Goldberg, 1989). Genetic algorithms use the ideas of natural selection and genetics to optimize non-linear functions. Genetic algorithms' performance is frequently better than conventional methods since they are population-based and use global search strategies (Fogel, 1994). Figure 13 depicts the basic phase cycle employed by genetic algorithms.

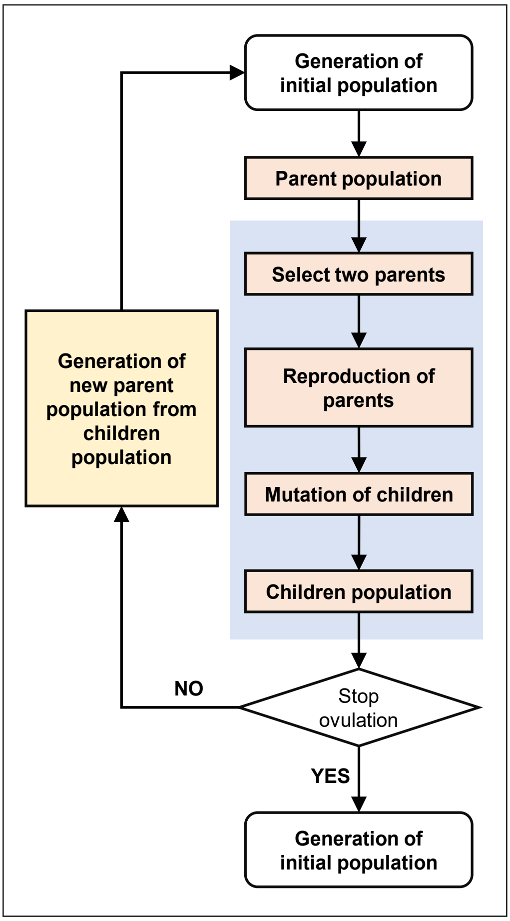


Figure 13. Steps in genetic algorithm (Rahimi & Nazemizadeh, 2014)

Differential Evolution Algorithm Method

To solve a certain class of issues, such as Linear Programming Problems (LPP), Integer Programming Problems (IPP), Quadratic Programming Problems (QPP), Non-convex Optimization, and many more, optimization is a decision-making process (Pant et al., 2020). Differential Evolution (DE), an optimization technique used to improve the fuzzy-PID controller, is also discussed. The Evolutionary Algorithms

(EAs), a large family of stochastic optimization algorithms motivated by biology, are connected to DE (Sloss & Gustafson, 2020). The first chromosome serves as the basis value for the mutant chromosome, and the scaler (F) is created by multiplying the difference between the second and third chromosomes. The DE mutation method commonly has the following format: "DE/*/n," where "*" denotes the target vector taken into account throughout the mutation process and "n" denotes the number of different vectors involved. During the crossover step, the target and mutant vectors cross probabilistically to produce an offspring or trial vector. Through this crossover process, the target solution may acquire the features of the donor solution or mutant. The uniform crossover technique is controlled by a Crossover Rate (CR) with a value between [0,1]. Local and global selections are two distinct selection types (Figure 14).

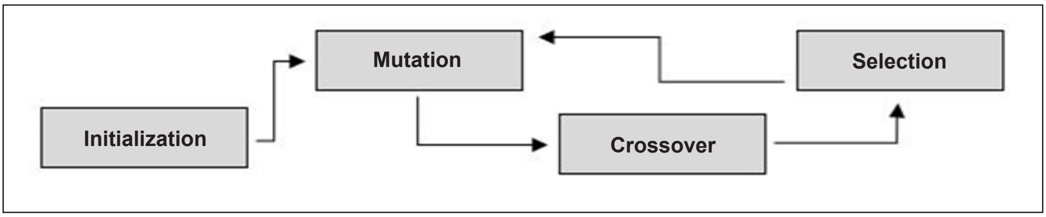
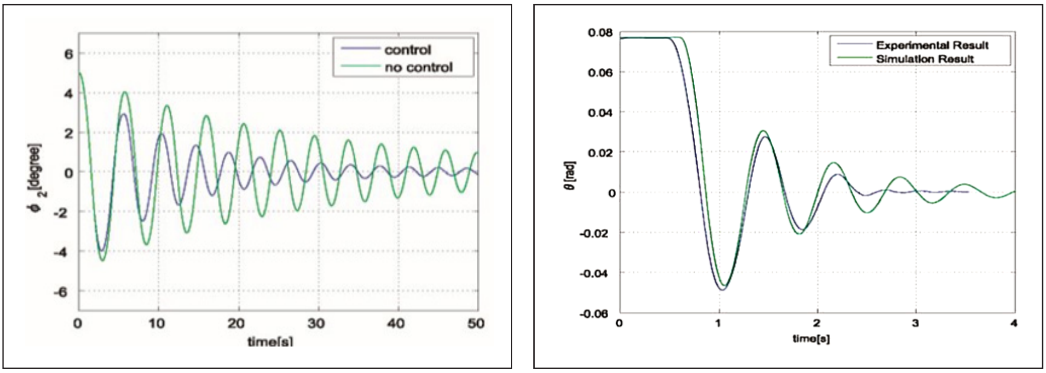


Figure 14. DE consecutive phases

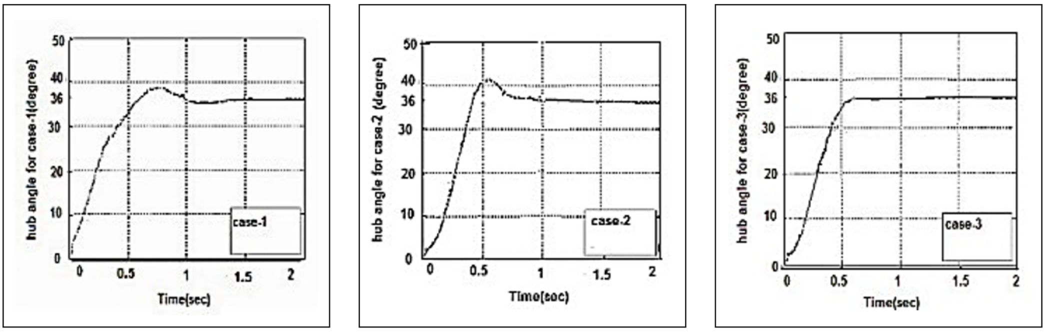
RESULTS AND DISCUSSION

The Single, Double, and Multi-Link Flexible Manipulators, especially in the SLFM, were the subject of this paper's assessment of various approaches for analysis, mathematical and dynamical modeling, mechanical vibration control strategies, and optimization methods of Robotics Flexible Manipulator (RFM) structures. A published paper may simply address the implementation of a controller and optimizations on the FLM as a sophisticated test bed. Figures 15 and 16 and Tables 1, 2, 3, 4, 5, 6 and 7 provide general findings and signals.



(a) (b)

Figure 15. (a) Typical signals of vibration control result in 1; and (b) vibration control results in 2 (Hirano et al., 2010)



(a) (b) (c)

Figure 16. Mechanical vibration control of typical RFM structures in step response (Zebin & Alam, 2010): (a) Result 1; (b) Result 2; and (c) Result 3

Table 1

Parameters for link 1 of a typical RFM structures

No	Parameters for link 1	Values
1.	No of element, N_i	1
2.	Length, L_i	0.9 m
3.	Mass density per unit volume, P_i	2710 kg/m^3
4.	Cross sectional area, A_i	6.0833×10^{-5} m^2
5.	Youngs modules, E_i	7.11×10^{10} N/m^2
6.	Second moment of area, I_i	5.2530×10^{-11} m^4

Table 2

Parameters for link 2 of a typical RFM structures

No	Parameters for link 2	Values
1.	No of element, N_i	1
2.	Length, L_i	1.1 m
3.	Mass density per unit volume, P_i	2710 kg/m^3
4.	Cross sectional area, A_i	6.0833×10^{-5} m^2
5.	Youngs modules, E_i	7.11×10^{10} N/m^2
6.	Second moment of area, I_i	5.2530×10^{-11} m^4

Table 3

Results for link 1 of a typical RFM structures

No	Control Strategy	Over Shoot (%)	Rise Time (s)	Settling Time (s)	Steady State Error
1.	Case 1	9.11	0.62	1.2392	0
2.	Case 2	13.45	0.46	0.9866	0
3.	Case 3	0	0.5	0.5496	0

Table 4

Results for link 2 of a typical RFM structures

No	Control Strategy	Over Shoot (%)	Rise Time (s)	Settling Time (s)	Steady State Error
1.	Case 1	8.22	0.56	1.4432	0
2.	Case 2	15.5	0.31	0.9466	0
3.	Case 3	0	0.37	0.5192	0

Table 5

Dynamic analyses and dynamical problem and complexities involved in a two-link flexible manipulator

No	Dynamic Analyses	Related Papers
1	Dynamic strength and reliability analyses	Castri and Messina (2010)
2	Energy scavenger	Dogan (2012)
3	Symmetric dichotomy-based model	Li and Wang (2000)
4	Vibration suppression	Karagulle et al. (2015)
5	Approximate dynamic model	Tomei and Tornambe (1988)
6	Eigenvalue problem analyses	Castri and Messina (2010)
7	Flexible space manipulator	Chu and Cui (2012)
8	Wheel suspended flexible manipulator	Yuwei et al. (2011)
	Dynamical problems and Complexities	
9	Control Complexities a. non-minimum phase	Chen and Paden (1996)
10	Control Complexities b. Underactuation	Bergeman (1996)
11	Control Complexities Non-collocation	Karkoub et al. (1995)
12	MIMO system	Wang and Gao (2003)
13	Uncertainties a. Truncation of flexible modes	Zhang et al. (2004)
14	Uncertainties b. Control spillover	Khorrami and Jain (1992)
15	Uncertainties Eigenvalues problem	Book et al. (1975)
16	Uncertainties c. Observation spillover	Khorrami and Jain (1992)

Table 6

Applications of the DE algorithm and methods with other artificial intelligent algorithms

No	DE Applications	Years	Related Papers
1	Prediction	2018	(Peng et al., 2018)
2	Feature selection	2018	(Yao & Ge, 2018)
3	Image processing	2020	(Sui et al., 2020)
4	Clustering	2019	(Ahmad et al., 2022)
5	Health care	2019	(Wang et al., 2019)
6	Path planning	2020	(Chellaswamy et al., 2019)
	DE Methods		
7	with ANN	2018	(Mason et al., 2018)
8	with CS	2019	(Zhang et al., 2019)
9	with PSO	2019	(Wang et al., 2019)
10	with WOA	2018	(Xiong et al., 2018)

Table 7
Available techniques and modeling methods

No	Modeling method	Problems	Schemes	Related Papers
1	Lumped parameter	Position control Vibration suppression	Classical control	Khorrami and Sandeep (1994)
2	Lumped parameter	Tip position control Vibration suppression	Robust control	Lochan and Roy (2015)
3	Lumped parameter	Trajectory	Robust control	Bossert et al. (1995)
4	Lumped parameter	Position control Tip trajectory tracking	Robust control	Theodore and Ghosal (2003)
5	Assumed modes	Trajectory tracking Vibration suppression	Classical control	Mahamood and Pedro (2011)
6	Assumed modes	Position control	Classical control	Chen et al. (2011)
7	Assumed modes	Position control Vibration suppression	Classical control	Fukuda and Arakawa (1987)
8	Assumed modes	Tip position control Trajectory tracking	Robust control	Bai et al. (1998)
9	Finite element	Tip position control Trajectory tracking	Classical control Robust control Intelligent control	Zhang et al. (2004)
10	Finite element	Tip position control Vibration suppression	Classical control Robust control Intelligent control	Zebin and Alam (2010)
11	Finite element	Trajectory tracking	Robust control	Schoenwald et al. (1991)
12	Finite element	Position control Vibration suppression	Robust control	Liu and Zhang (2013)
13	Non-parametric	Position control	Classical control	Vandini et al. (2014)
14	Non-parametric	Position control Vibration suppression	Hybrid control	Maouche and Meddahi (2016)
15	Non-parametric	Trajectory tracking	Robust control Intelligent control	Yazdizadeh et al. (2000)
16	Non-parametric	Position control Vibration suppression	Classical control	Chu and Cui (2015)

CONCLUSION

This survey of the literature on state-of-the-art flexible manipulators demonstrates that dynamic analysis and control of Flexible Link Manipulators (FLM) is a developing field of study in manufacturing, automation, and robotics. Applications span simple pick-and-place operations of an industrial robot to microsurgery, maintenance of nuclear reactors, and space robotics. In fact, there is no assurance that a published article presents a way superior to alternative theories of manipulator control. Figure 17 provides general findings, charts, signals, and summaries, as shown below. In fact, there is no assurance that a published

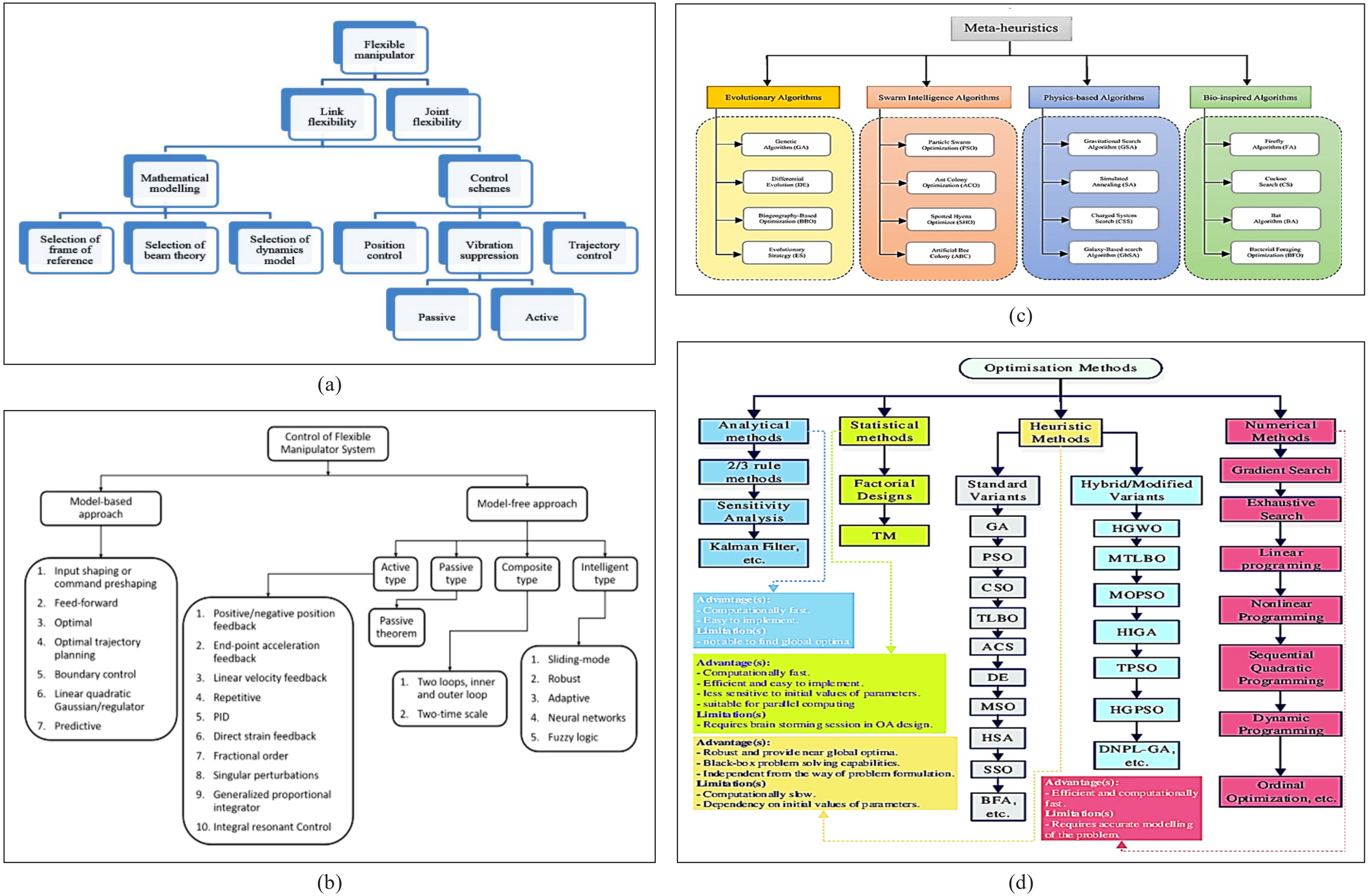


Figure 17. (a) Mathematical and dynamical modeling; (b) Mechanical vibration control strategies; (c) Metaheuristics; and (d) Optimization methods

article presents a way superior to alternative theories of manipulator control. The specific results registered in the world and Europe are classified in journals and publications as research papers such as modeling and controlling flexible manipulators (Alandoli et al., 2016; Fukuda & Arakawa, 1987; Pereira et al., 2014), optimal control strategies for flexible manipulators (Ge et al., 1996), vibration suppression of flexible manipulators (Karagulle et al., 2015), optimal trajectory planning for flexible manipulators (Atef et al., 2012; Liu & Zhang, 2013) in conferences as International Conference on Robotics and Automation (ICRA) and International Symposium on Flexible Automation (ISFA). Results of publications of researchers and experts working in modern methods in the field of machine modeling and simulation as a research and practical issue related to Industry 4.0 registered in the world are classified in journals and conferences as research papers such as Cyber-Physical Systems architecture (Lee et al., 2015), Enterprise systems with State-of-the-art and future trends (Li et al., 2018), Undesirable Emergent Behavior in Complex Systems (Grieves & Vickers, 2017).

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