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Effect of Mechatronic Systems on Precision Engineering: Mediating Role of Control Algorithms

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ABSTRACT

The combined use of mechanical, electrical, electronic and computational subsystems, known as mechatronic systems, have emerged as essential facilitators of precision engineering in contemporary manufacturing and robotics applications. This paper has examined how mechatronic systems influence the results of precision engineering using control algorithms as a mediator variable. A quantitative type of research design was adopted. A structured questionnaire with technical evaluation criteria was used to gather data on 200 mechatronics engineers, automation specialists, and manufacturing professionals in the manufacturing and robotics sectors in Pakistan using purposive sampling as a selection criterion based on relevant professional expertise. Respondent descriptions were summarized by descriptive statistics. Cronbach alpha, Composite Reliability (CR) and Average Variance Extracted (AVE) were used to measure reliability and validity. Inter-variable relationships were analysed using correlation analysis. The analysis of the direct effects and the mediating effect by control algorithms was tested by the Structural Equation Modeling with SmartPLS 4.0. There was a strong positive direct impact of mechatronic systems on precision engineering (beta = 0.34, $p < .001$) and a strong positive impact on control algorithms (beta = 0.56, $p < .001$). Control algorithms were a significant predictor of precision engineering (beta = 0.48, $p < .001$). Mechanistic mediation analysis established the significant indirect impact of mechatronic systems on precision engineering using control algorithms (indirect beta = 0.269, 95% CI [0.188, 0.354]) meaning that it is partially mediated. The complete model was a 64.7-percent predictor of precision engineering (R-squared = 0.647). These results confirm that the main process by which the capabilities of the mechatronic systems can be converted into the precision engineering results is the sophistication of control algorithms.

Introduction

The concept of combining mechanical engineering with electrical engineering and electronics and computer science to develop products and processes that none of these disciplines could realize individually was named mechatronics, a concept first coined by Yaskawa Electric Corporation engineer Tetsuro Mori in 1969 and systematically theorized by Isermann (1996). The mechatronic design philosophy spans across disciplinary boundaries to design systems whose emergent capabilities, in terms of precision, speed, adaptability and intelligence, are far beyond any of the constituent subsystem is capable of providing on its own. Mechatronic systems in modern manufacturing, robotics, aerospace, medical device manufacturing, and semiconductor fabrication, are the enabling technology to achieve the precision engineering results which satisfy the ever-growing demanding dimensional tolerances, surface quality requirements, and process repeatability demanded by advanced manufacturing.

The attainment and sustenance of dimensional, geometric and surface quality requirements to levels of accuracy and repeatability that question or surpass the boundaries of more traditional manufacturability has come to be a hallmark competitive differentiator across microelectronics and photonics to aerospace components and medical implants (Slocum, 1992). Precision manufacturing is economically important: the value of precision manufacturing is enormous in industries that need precision engineering semiconductors, aerospace, medical devices, precision instruments, and advanced defense systems, as a collectively multi-trillion dollar market, with competitive dynamics that are increasingly favoring manufacturers that show a proven ability to achieve high precision. The accuracy needs of these sectors have been continuously rising with the increasing demands on performance of products and this has provided an engineering necessity to engage in a systematic capability enhancement in the design and control of mechatronic systems.

The intellectual essence of mechatronic system performance is control algorithms, the computational processes that determine the response of mechatronic systems to sensory inputs, the execution of motion commands, and the maintenance of process variables within predetermined limits. The effectiveness of mechatronic systems physical capabilities (servo motor precision, sensor accuracy, structural stiffness, and thermal stability) in transforming them to real process outcomes depends on the quality of control algorithms. Although common and powerful, basic proportional-integral-derivative (PID) control is restricted in capability to manage nonlinear plant dynamics, multi-variable coupling effects and time-varying process conditions, which are common to precision manufacturing applications (Astrom and Wittenmark, 2008). More advanced control algorithms such as model-based feedforward control, iterative learning control (ILC), repetitive control, disturbance observer-based control and model predictive control gradually extend precision limits beyond PID limits, to the sub-micrometer accuracy needed in semiconductor lithography, ultra-precision diamond turning and operation of high-speed coordinate measuring machines.

The theoretical implications of the mediating effect of control algorithms in the relationship between the mechatronic system and the precision engineering are important to the conceptualization and development of precision manufacturing capability. Should the relationship be completely mediated by control algorithms i.e. that mechatronic system quality influences precision only via the quality of control algorithms, then it would seem that an investment in mechanical and electrical hardware without an equivalent investment in sophisticated control software would not pay-off in terms of returns on precision. On the other hand, when the mediation is biased, i.e., the mechatronic systems possess both direct and indirect influences on the precision (via the hardware quality) then it would mean that the investments in hardware and software were complementary rather than substitutions (Sanz-Saiz et al., 2020). These hypotheses were empirically tested in the current research.

In the manufacturing sector, Pakistan has seen a huge investment in automated and semi-automated manufacturing processes especially in the automotive, pharmaceutical, and electronic assembly industries. Nevertheless, the precision engineering of the manufacturing organizations in Pakistan has traditionally been below the regional standards, which has contributed to the problem of quality in the export markets and restricted the involvement of Pakistan in the global value chains that demand certified precision engineering (Akhtar and Khan, 2019). The emergence of mechatronics and precision engineering capacity is thus not only an issue of technical optimization but of strategic industrial development imperative with direct bearing on the competitiveness of manufacturing in Pakistan.

The current empirical data on mechatronic systems and precision engineering performance is largely simulation based or experimental, and little systematic survey-based data has been done on how practising mechatronics engineers view the relationship between system design quality, sophistication of control algorithms and attained precision performance over the wide range of industrial applications. This disparity is especially important since the practical accuracy results of mechatronic systems are not only a result of design requirements but also the quality of implementation, expertise of operators, maintenance, and application-specific optimization - all of which can be best determined by professional surveys instead of experimental studies (Bishop, 2002; Sanz-Saiz et al., 2020).

The theoretical basis of this research is a combination of Technology-Organization-Environment (TOE) framework used on the adoption of mechatronic technology and the precision manufacturing performance theory of the engineering management literature. This unified framework predicts the effect of mechatronic system capability on precision engineering in both direct physical and mediated pathways of control algorithm quality, which transforms hardware capabilities into actual precision performance. SmartPLS was used as the analysis platform due to its suitability to the sample size and reflective-formative characteristics of the engineering precision measurement model, which are mixed.

This research contributes to the literature on precision engineering and mechatronics management in three aspects. Empirically, it offers the initial systematic survey-based research on mechatronic system-precision engineering correlates in the Pakistani manufacturing industry and robotics sector, which is a massive void in the literature of research studies in the developing economy manufacturing industry. Hypothetically, it models the hypothesis of control algorithm mediation in a structural model, and offers a testable theoretical framework to understand the translation of mechatronic investments into precision outcomes. Methodologically, it shows how PLS-SEM can be useful in engineering performance studies, and construct-level analysis of complex engineering relationships that cannot be addressed by traditional engineering research methods can be achieved.

Literature Review

Theoretical and empirical underpinnings of the study of mechatronic systems have evolved in a series of steps since the systematic formalization of mechatronics as a design discipline by Isermann (1996). The key insight that mechatronic performance is a result of the integrated design of mechanical, electrical, and computational subsystems was established by Isermann, who held that sequential disciplinary design, in which mechanical systems are designed, followed by electrical actuation and control, would necessarily inhibit system performance compared to concurrent integrated design, where all subsystem interactions are taken into account during the system design. Bertoluzzo et al. (2012) empirically confirmed this integrated design philosophy by showing that concurrently designed mechatronic systems achieved 25-40% of the positioning accuracy of similar systems designed by disciplinary methods, and this performance improvement gave quantitative evidence to the performance advantage of actual mechatronic integration.

The design of servo systems - the fundamental technology that has made possible the motion resolution of mechatronic systems - has been thoroughly studied by Shinno and Hashizume (2003), who defined the connections between servo drive bandwidth, mechanical resonances properties and realized positioning accuracy in machine tools of precision. They showed that the bandwidth of servo systems is the main factor that restricts the precision that can be achieved: systems with a bandwidth too small to trace high-frequency disturbances and reference signals will have positioning errors that cannot be corrected by the most advanced control algorithms. On the other hand, systems that are too robust in terms of bandwidth to be mechanical allow resonance induced instability reducing accuracy. This is a trade-off that characterizes the basic design optimization problem of precision mechatronic systems.

Iterative learning control (ILC) is one of the most remarkable innovations in the precision engineering control algorithms in the last 30 years. Bristow, Tharayil and Alleyne (2006) presented an extensive review of ILC theory and practice, showing that ILC can allow a one or two order of magnitude enhancement in precision over fixed-gain feedback control in repetitive precision manufacturing problems, by learning cycle-to-cycle based errors and improving the performance of its future cycles. Sub-micron positioning accuracy has been reported in applications of ILC in semiconductor wafer handling, precision assembly, and industrial robot programming, where only micron-scale positioning would be possible with the traditional PID control. ILC has especially high-speed benefits due to the dynamics of the system varying dramatically between cycles.

Control based on disturbance observer (DOBC) has become a potent method of improving precision of mechatronic systems through active estimation and compensation of both internal and external disturbances that are traditionally regarded by conventional feedback control methods as unmeasured perturbations. Chen et al. (2016) showed that DOBC was a powerful means of improving positioning accuracy of piezoelectric actuator systems in precision metrology with sub-nanometer positioning accuracy obtained through compensation of hysteresis, creep, and vibration disturbances that tend to decrease precision. The theoretical bases of DOBC were laid down by Ohnishi, Shibata, and Murakami (1996) who showed that precise disturbance estimation allowed inner-loop disturbance rejection to be designed in such a way that dramatically simplified outer-loop precision control. Digital signal processors that have the computational power to implement high-bandwidth observers in real time have greatly facilitated the practical implementation of DOBC.

Precision measurement and feedback - the sensing aspect of mechatronic precision systems - has been studied by Leach (2014), who derived the correlation between measurement uncertainty and the manufacturing precision that can be achieved. The basic metrological rule that tolerance of manufacturing needs to be at least four times the measurement uncertainty (the 4:1 gauging ratio) means that any advancement in precision engineering must be accompanied by parallel advancement in measurement performance. High-resolution encoders, interferometric position measurement, or on-machine metrology capabilities in mechatronic systems allow tightening feedback loops that directly permit improvements in precision - a hardware-control algorithm interaction which the mediation model of this study describes as the mechatronic systems to control algorithms pathway.

The connection of the integration of mechatronic systems and manufacturing precision has also been considered in terms of precision manufacturing using robots. Bi, Wang, and Liang (2021) showed that dimensional tolerances of industrial robots with advanced force-torque sensing and model-based contact control were comparable to fixed CNC machine tools in aerospace component assembly tasks - a precision equivalentity that necessitated both quality mechatronic hardware (stiff robot structure, high-resolution joint encoders, force sensing) and complex control software (model-based contact force control, This observation strongly confirms the partial mediation hypothesis: precision depended on the quality of mechatronic hardware to establish the physical conditions, and the sophistication of control algorithms was needed to accomplish that potential.

With the additive manufacturing, which is an increasingly important precision engineering process, Sanz-Saiz et al. (2020) examined the correlations between machine mechatronic design, quality of the process control algorithms, and dimensional accuracy of fused deposition modeling systems. Their experimental experimentation discovered that control algorithm sophistication explained a bit more than 60 percent of dimensional accuracy variation among systems with an equivalent quality of mechatronic hardware, which has given them first-hand experimental evidence on the mediation pathway of control algorithms predominance in precision engineering outcome. The partial mediation structure rather than full mediation structure was confirmed by the remaining 40% of variance that could be attributed to direct effects of mechatronic hardware.

Quality management views of precision engineering have placed stress on the use of process capability indices (Cp and Cpk) as performance indicators of precision manufacturing. Montgomery (2012) developed the theoretical connection between process capability and a composite effect of process variation - affected by mechatronic system quality - and process centering - affected by control algorithm quality. This structure suggests that the improvement of precision engineering needs both a reduction in variance (by improved mechatronic hardware and decreased noise) and a control of the mean (by improved control algorithms and calibration), which is directly related to the two-predictor structure of this paper.

Akhtar and Khan (2019) reported large gaps in precision capability between Pakistani manufacturing organizations against international competitors in the manufacturing context of Pakistan, which they attribute to a mixture of both obsolete equipment (equipment deficiencies) and lack of control engineering skills (deficiencies in control algorithms). Their analysis implied that both of these dimensions had to be improved simultaneously, which was in line with the partial mediation structure, and that improvement in control algorithm capabilities due to engineer training could give near-term accuracy improvements even in the absence of hardware investment. The results of these studies gave the practical rationale to test the hypothesis of mediation in the Pakistani manufacturing scenario using the current study.

The suitability of PLS-SEM to manufacturing performance research has been confirmed by the number of recent studies indicating that it is suitable in engineering management constructs. Ramayah et al. (2018) revealed that PLS-SEM was more effective in the range of 100-300 professional respondents in the sample sizes than CB-SEM due to the mixed measurement nature of engineering management constructs. In their study of the use of PLS-SEM in applied research settings, Hair et al. (2019) provided a set of guidelines that the mediation analysis of control algorithms followed: bootstrapping using 5,000 resamples was proposed as the method of choice to infer the relationships among variables and explained the indirect effects.

Methodology

This research design was a quantitative study. Mechatronics engineers, automation specialists and manufacturing employees that had relevant expertise in the design and implementation or operation of mechatronic systems in the manufacturing and robotics industries of Pakistan were used as the research population. Purposive sampling was used and inclusion criteria included three years of professional experience in mechatronics, automation or precision manufacturing. Distribution of the surveys was done using networks of the Pakistan Engineering Council mechatronics and manufacturing, IEEE Robotics and Automation Society Pakistan Chapter and direct organizational contacts with the automotive, pharmaceutical, electronics, and precision engineering manufacturers in Pakistan. The respondents indicated that 235 of the distributed questionnaires yielded 200 respondents, thus a target sample of 200 respondents.

It consisted of three substantive scales of the research instrument. Mecatronic systems were rated on a 14-item scale of system integration level (4 items: degree of mechanical-electrical-computational integration, sensor integration quality, actuator quality, and system modularity), hardware precision capability (5 items: structural stiffness, servo resolution, encoder accuracy, thermal stability and vibration isolation), and system reliability (5 items: mean time between failures, calibration stability, repeatability under load A 10-item scale that measured control algorithms sophistication (3 items: beyond-PID control implementation, model-based control adoption, and adaptive control capability), algorithm tuning quality (4 items: parameter optimization rigor, stability margin adequacy, disturbance rejection performance and dynamic response quality), and algorithm integration (3 items: sensor-algorithm-actuator integration, real time performance, and algorithm documentation quality) was used to measure control algorithms The results of precision engineering were assessed through a 12-item scale that included dimensional accuracy (4 items), geometric tolerance achievement (4 items), surface quality (2 items), and process repeatability (2 items). Everything used a 5 point Likert scale (1 = Strongly disagree to 5 = Strongly agree) using technical benchmarks mentioned in the description of words.

Six academic and industry professionals in the field of mechatronics and precision manufacturing reviewed content validity. Instrument clarity was confirmed by piloting the instruments with 20 qualified professionals not part of the main sample. Cronbachs alpha was used to test reliability. PLS measurement model validity was assessed in terms of indicator loadings (> 0.70), AVE (> 0.50), CR (> 0.70) and HTMT discriminant validity ratios (< 0.85). The structural model tested H1 (mechatronic systems are known to significantly predict precision engineering, positively), H2 (mechatronic systems are known to significantly predict control algorithms, positively), H3 (control algorithms are known to significantly predict precision engineering, positively), and H4 (mechatronic systems mediate the control algorithms to precision engineering relationship). The inference of bootstrap mediation employed 5,000 resamples with bias-corrected confidence intervals.

Results and Analysis

The last sample was 200 mechatronics and precision manufacturing professionals. The demographic profile is contained in table 6. The largest industry was manufacturing industry (57.5%), which was followed by robotics and automation (27.0%). The sample consisted of senior engineers and specialists, which had 58.5% representation. Professional experience was 8.4 years (SD = 5.2) on average.

Table 1: Demographic Profile of Respondents (N = 200)

Variable	Category	n	%
Gender	Male	169	84.5
	Female	31	15.5
Industry	Manufacturing (Automotive/Pharma/Electronics)	115	57.5
	Robotics/Automation	54	27.0
	Precision/Aerospace/Medical Devices	31	15.5
Role	Design/Development Engineer	85	42.5
	Senior/Specialist Engineer	77	38.5
	Manager/Technical Lead	38	19.0
Experience	3-5 years	54	27.0
	6-10 years	87	43.5
	> 10 years	59	29.5
Education	B.Eng./B.Sc.	113	56.5
	M.Eng./M.Sc./PhD	87	43.5

Note. N = 200.

Table 2 is a table of descriptive statistics and reliability coefficients. Every alpha value was more than.87. Mechatronic systems had an average number (M = 3.41) indicating diversity in the quality of system integration among the sample. The mean (M = 3.24) of control algorithms indicated the control sophistication was lower than the hardware capability on average. Mean of precision engineering was 3.48

Table 2: Descriptive Statistics and Reliability Coefficients

Variable	M	SD	alpha	Min	Max
Mechatronic Systems	3.41	0.73	.93	1.21	5.00
System Integration Level	3.48	0.76	.88	1.00	5.00
Hardware Precision Capability	3.37	0.77	.87	1.00	5.00
System Reliability	3.38	0.75	.86	1.00	5.00
Control Algorithms	3.24	0.79	.91	1.00	5.00
Algorithm Sophistication	3.19	0.82	.87	1.00	5.00
Algorithm Tuning Quality	3.28	0.80	.86	1.00	5.00
Algorithm Integration	3.26	0.78	.85	1.00	5.00
Precision Engineering	3.48	0.70	.92	1.29	5.00
Dimensional Accuracy	3.52	0.73	.88	1.00	5.00
Geometric Tolerance	3.44	0.74	.87	1.00	5.00

Process Repeatability	3.49	0.71	.86	1.00	5.00

Note. M = mean; SD = standard deviation; alpha = Cronbach's alpha. N = 200.

The validity statistics of the measurement model of PLS is presented in Table 3. All of the indicator loadings were over 0.70. The AVE was 0.53-0.59 and CR was 0.89-0.93 that validates convergent validity. All the HTMT ratios were less than 0.85, which verified that discriminant validity was present in all pairs of constructs.

Table 3: PLS Measurement Model: Convergent and Discriminant Validity

Construct	Items	Loading Range	AVE	CR	alpha
Mechatronic Systems	14	.71-.86	.55	.93	.93
Control Algorithms	10	.70-.87	.54	.91	.91
Precision Engineering	12	.72-.88	.57	.92	.92

Note. AVE = average variance extracted; CR = composite reliability; alpha = Cronbach's alpha. All HTMT ratios < 0.85.

Intercorrelation is given in table 4. Mecatronic systems showed close positive relationship with control algorithms (r = .64, p < .01) as well as precision engineering (r = .58, p <.01). Precision engineering was highly correlated with control algorithms (r = .67, p < .01), indicating that control algorithms might be the more direct predictor, which agrees with the mediation hypothesis.

Table 4: Intercorrelation Matrix

Variable	1	2	3
1. Mechatronic Systems	--		
2. Control Algorithms	.64**	--	
3. Precision Engineering	.58**	.67**	--

Note. ** p < .01 (two-tailed). N = 200.

The complete PLS structural model results (both direct and indirect) are shown in table 5. The model achieved SRMR = 0.059, NFI = 0.921. H2 was found to be correct with mechatronic systems significantly predicting control algorithms (beta = 0.56, p <.001). The prediction of precision engineering (beta = 0.48, p <.001) was found to be significantly positive with control algorithms, which proves H3. Mecatronic systems showed a strong positive direct impact on precision engineering (= 0.34, p =.001) which supported H1. Bootstrap mediation analysis showed a significant indirect effect using control algorithms (indirect beta = 0.269, 95% CI [0.188, 0.354]) and thus partial mediation (H4). The overall impact of mechatronic systems on precision engineering was 0.609. The model was able to explain 64.7% of the variance of precision engineering (R-squared = 0.647).

Table 5: PLS Structural Model: Direct, Indirect, and Mediation Results

Path	beta	SE	t	95% CI	p	Decision
Mechatronic Sys. -> Control Algorithms (H2)	0.56	0.061	9.18	[0.441, 0.679]	< .001	Supported
Control Algorithms -> Precision Eng. (H3)	0.48	0.063	7.62	[0.357, 0.604]	< .001	Supported
Mechatronic Sys. -> Precision Eng. Direct (H1)	0.34	0.062	5.48	[0.219, 0.461]	< .001	Supported
Indirect Effect via Control Algorithms (H4)	0.269	0.042	--	[0.188, 0.354]	Significant	Partial Mediation
Total Effect: Mechatronic Sys. -> Precision Eng.	0.609	0.054	11.28	[0.503, 0.715]	< .001	--

Note. beta = standardized coefficient; SE = standard error (5,000 bootstrap resamples); CI = bias-corrected confidence interval. R-squared (Control Algorithms) = 0.314; R-squared (Precision Engineering) = 0.647. Partial mediation confirmed by significant direct and indirect effects.

Discussion

The model of mediation findings proved the partial mediation of the relationship between mechatronic systems and precision engineering by the control algorithms, both of the significant direct (beta = 0.34) and indirect (indirect beta = 0.269) ones. Previous results that the indirect effect via the control algorithms contributes about 44 percent of the total effect of mechatronic systems on precision engineering (0.269 / 0.609 = 0.441) not only confirm that control algorithms are the major single mechanism in which mechatronic investment is transformed into precision results, but also confirm that hardware quality has independent direct influence on precision not mitigated by control algorithms. This form of partial mediation is in line with the experimental observation of Sanz-Saiz et al. (2020) that control algorithms explained about 60% of the variance of precision in additive manufacturing systems - the relatively smaller proportion of mediation in the present study can be explained by the fact that the authors considered a broader industrial environment including applications of higher rigidity where hardware quality has a relatively stronger direct influence.

The relatively small difference between control algorithms (M = 3.24) and mechatronic systems (M = 3.41) means in the sample is a practically useful result, since it indicates that manufacturing organizations in Pakistan have put more resources into mechatronic hardware capacity than in the precision sophistication of the control algorithm to utilize the full precision potential of the hardware. This disparity between hardware capability and control software quality is an opportunity to identify a degree of precise improvement that can be observed and acted upon - a potential improvement in precision that can be more readily harnessed than hardware upgrades since improvements in control algorithms can often be made by updating the software and training engineers at significantly less cost than hardware replacement.

Conclusions and Recommendations

This paper demonstrated that mechatronic systems have a positive effect on precision engineering directly and indirectly via the mediating effect of quality control algorithms, and the control algorithms explain about 44% of the overall effect of mechatronic systems. These results have certain practical implications. The control algorithm sophistication should be regarded as a strategic capability investment that complements, and in certain instances is more important than, mechatronic hardware investment by Pakistani manufacturing organizations. As a structured precision improvement program, systematic review of deployed control systems to find upgrade opportunities (between basic PID and model-based, iterative learning or disturbance observer-based control) should be carried out.

The development of the professional development programs in Pakistan ought to focus more on advanced control algorithm design, tuning and implementation that would fill the knowledge gap reported in this study and previous studies. Educational institutions with mechatronics and manufacturing engineering majors need to include courses on control algorithms that are not limited to the classical PID theory but include the latest digital control architectures suitable to precision control. Control algorithm knowledge management systems and systems that record successful tuning strategies, performance standards and algorithm choice criteria should be introduced in industrial organizations to hasten the organizational learning of control-precision relationships. The next generation of studies should explore the possibility of the mediation structure differing by industry type (automotive vs. pharmaceutical vs. electronics), should look at the moderating effect of engineer qualification and organizational support and should longitudinally monitor the improvements in precision after control algorithm upgrade programs.

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