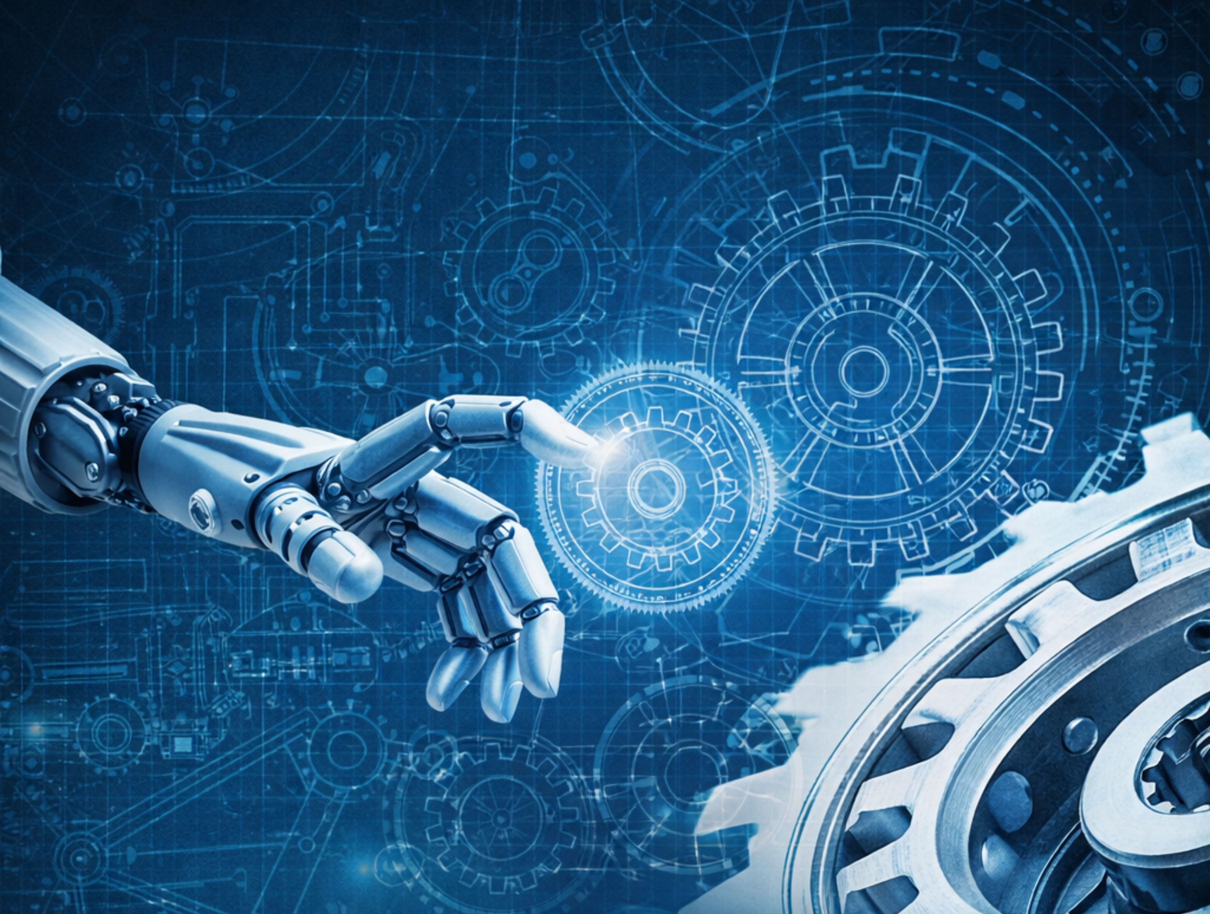

ADVANCES IN MECHANICAL ENGINEERING AND ROBOTIC SYSTEMS

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PREFACE

This book brings together a set of interdisciplinary studies that examine contemporary challenges in engineering, operations, and intelligent systems. The chapters reflect a shared focus on analytical rigor, practical problem-solving, and the application of modeling and decision-support techniques to complex technical and organizational contexts.

The opening chapter, Modeling Short-Range Artillery Trajectories with Progressive Drag and Wind Effects, presents a detailed analytical approach to understanding motion dynamics under real-world conditions. By incorporating environmental and physical variables, it demonstrates how advanced modeling enhances accuracy, prediction, and operational effectiveness in engineering and defense-related applications.

Shifting from physical systems to organizational decision-making, the chapters Evaluating the Efficacy of Equipment Rehabilitation versus Procurement of New Assets in Organizational Operations and My Vehicle Was Fine Yesterday: An Investigation into Sudden Mechanical Failures and Poor Fleet Monitoring address asset management and operational reliability. Together, they emphasize the importance of maintenance strategies, data-driven monitoring, and informed investment decisions in sustaining performance and minimizing unexpected failures.

The final chapter, Approaches to the Design and Programming of Robotic Systems in Production Process, explores the integration of automation and intelligent control within modern manufacturing environments. It highlights key design principles and programming strategies that support efficiency, precision, and adaptability. Collectively, these chapters offer readers valuable insights into the intersection of engineering analysis, operational management, and advanced production technologies.

Editorial Team
January 26, 2026
Türkiye

CHAPTER 1
MODELING SHORT-RANGE ARTILLERY TRAJECTORIES WITH PROGRESSIVE DRAG AND WIND EFFECTS

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INTRODUCTION

Artillery trajectory prediction has historically represented a central challenge in applied mechanics, particularly prior to the advent of digital computation. During the eighteenth and nineteenth centuries, artillery officers relied on analytical reasoning, geometric methods, and empirical firing tables to estimate projectile paths under the influence of gravity, aerodynamic drag, and wind (McCoy, 1999; Mayevski, 1881; Siacci, 1901). The present study revisits this classical problem using modern physical principles but restricts the computational tools to those available to a mathematically trained officer of that era.

The cannon considered is representative of heavy field artillery used approximately two centuries ago. It fires a spherical projectile of mass 5 kg and diameter 0.11 m (approximately 4.3 in) with a maximum muzzle velocity of 450 m/s. The first objective is to determine the firing angle and muzzle velocity required to strike a target located 1,200 m away, assuming equal launch and target elevations of 500 m above sea level. Aerodynamic drag appropriate to a spherical projectile is included to ensure realistic results, in contrast to the idealized vacuum trajectory.

The analysis is then extended to targets at horizontal distances between 1,000 m and 1,500 m, incorporating the effects of headwinds and tailwinds (Levine, 1963). These factors represent the primary environmental influences affecting projectile range in field conditions. The broader objective is to develop a simplified, hand-calculable method that enables an artillery officer, without access to computational devices, to estimate the necessary muzzle velocity and firing angle rapidly and with reasonable accuracy.

This work therefore bridges historical artillery practice and modern physics, formulating a mathematically sound yet computationally simple approach suitable for manual application in the field.

1. ASSUMPTIONS AND NOTATIONS

Assumptions

Forces considered: The cannonball is affected only by gravity and aerodynamic drag during its flight.

Secondary effects such as Coriolis acceleration, Magnus lift due to spin, and turbulent gusts are neglected because their influence is small for short-range artillery and their inclusion would complicate manual methods unnecessarily.

Equal launch and impact altitude; planar motion: The cannon and the target are assumed to lie at the same elevation so that the motion is confined to a two-dimensional vertical plane $(x - y)$. Any height difference is taken as zero to simplify geometric relations.

Constant drag coefficient: The drag coefficient is treated as constant for the duration of the flight. For a smooth iron sphere, we adopt $C_d = 0.47$, a representative value for subsonic, near-spherical bodies (McCoy,1999).

Constant air density: Air density is taken constant and evaluated at the operating altitude (here $500\ \mathrm{m}$), with $\rho = 1.17\ \mathrm{kg\,m^{-3}}$. Because the projectile's trajectory height changes by only a few hundred metres, variations in ρ are neglected.

Flat Earth approximation: The Earth's curvature is ignored since the ranges considered (1.0–$1.5\ \mathrm{km}$) are negligible relative to the Earth's radius.

Point-mass projectile: The cannonball is treated as a rigid point mass; its internal structure, deformation, and rotation (except insofar as they might alter the effective drag coefficient) are neglected.

No wind in baseline model: The basic (baseline) trajectory calculations assume still air. Wind effects are treated separately in the wind-correction methods presented later.

Neglect of compressibility/transonic effects: Although the maximum muzzle speed considered ($\approx 450\ \mathrm{m/s}$) approaches or slightly exceeds the speed of sound, compressibility, shock formation, and the associated rapid changes in C_d are neglected for the baseline model (McCoy, 1999). This simplification is adopted to preserve analytic tractability and because the transonic interval is short relative to the total flight; however, the limitation is noted and discussed in the error analysis.

Table 1: List Of Symbols, Parameters, And Physical Constants Used in

Variable	Explanation	Unit / Value
m	Mass of the cannonball projectile	5 kg
D	Diameter of the spherical projectile	0.11 m
A	Cross-sectional area of the sphere ($A = \pi D^2/4$)	9.50×10^{-3} m^2
C_d	Drag coefficient of a smooth iron sphere	0.47
ρ	Air density at 500 m altitude	1.17 $\mathrm{kg/m^3}$
g	Acceleration due to gravity	9.81 $\mathrm{m/s^2}$
v_0	Muzzle velocity (initial projectile speed)	$100 - 450$ m/s
θ	Firing angle above the horizontal	$0° - 90°$
R	Target horizontal range	$1000 - 1500$ m
y	Vertical coordinate of projectile	m
x	Horizontal coordinate of projectile	m
k	Linear drag coefficient	$\frac{3\pi\mu D}{m}$ or numerically 0.012 s^{-1}
γ	Normalized linear drag parameter ($\gamma = k/m$)	s^{-1}
β	Quadratic drag coefficient ($\beta = \frac{C_d \rho A}{2m}$)	5.21×10^{-5} m^{-1}
v_x, v_y	Instantaneous horizontal and vertical velocity components	m/s
t	Time since firing	s
v_w	Wind velocity along the firing line (positive for tailwind, negative for headwind)	m/s
$v_{x,\mathrm{eff}}$	Effective horizontal velocity including wind ($v_x + v_w$)	m/s
f_w	Wind correction factor for effective muzzle velocity	Dimensionless
y_f	Final vertical displacement at impact (should be 0 for equal-altitude shots)	m
R_0	Baseline range (no wind, same altitude)	m
Δv_0	Required correction in muzzle velocity due to wind	m/s
Re	Reynolds number (Re $= \frac{\rho v D}{\mu}$)	Dimensionless
μ	Dynamic viscosity of air (at 500 m altitude)	1.78×10^{-5} Pa $\cdot$ s

2. RESEARCH AND FINDINGS

Assume that the cannonball is only affected by two main forces — gravity and aerodynamic drag — during its flight. Other minor effects such as Coriolis force, Magnus lift due to spin, and air turbulence are ignored since their influence is negligible for short-range artillery and can be neglected to simplify the calculation and facilitate model establishment.

Ideal Model Analysis

The ideal range formula is (Chudinov, 2001):

$$R = \frac{v^2 \sin(2\theta)}{g}$$

so, for a given muzzle speed v you must satisfy

$$\sin(2\theta) = \frac{gR}{v^2}.$$

This gives up to two complementary solutions for the elevation angle:

$$\theta_1 = 1/2 \arcsin\left(\frac{gR}{v^2}\right), \qquad \theta_2 = 1/2\left(\pi - \arcsin\left(\frac{gR}{v^2}\right)\right) = 90^\circ - \theta_1.$$

A solution exists only when $v^2 \geq gR$. The minimum muzzle speed (single solution, $\theta = 45^\circ$) is

$$v_{\min} = \sqrt{gR}.$$

By using $g = 9.81\ \mathrm{m/s^2}$ and $R = 1200\ \mathrm{m}$, $v_{\min} = \sqrt{9.81 \times 1200} \approx 108.50\ \mathrm{m/s}$ (at exactly 45.0°).

Below is a table of representative muzzle speeds v (m/s) and the corresponding two firing angles (degrees). If only one angle is shown it means the second solution coincides (the $v_{\min}$ case).

Notes

- For any $v \geq v_{\min}$ we get two complementary angles (low-angle and high-angle) that hit the same target; they sum to 90°.
- Projectile mass and diameter do not matter for the vacuum (no drag) solution.

Table 2. Launch Angles for Different Muzzle Velocities

v **(m/s)**	gR/v^2	θ_1 **(deg)**	θ_2 **(deg)**
108.499	1.0000	45.000	—
120.000	0.81750	27.418	62.582
140.000	0.60061	18.457	71.543

v **(m/s)**	gR/v^2	θ_1 **(deg)**	θ_2 **(deg)**
160.000	0.45984	13.689	76.311
180.000	0.36333	10.653	79.347
200.000	0.29430	8.558	81.442
220.000	0.24322	7.038	82.962
240.000	0.20438	5.896	84.104
260.000	0.17414	5.014	84.986
300.000	0.13080	3.758	86.242
350.000	0.09610	2.757	87.243
400.000	0.07358	2.110	87.890
450.000	0.05813	1.666	88.334

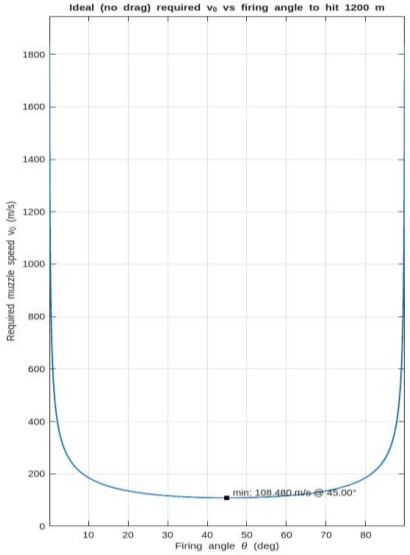

Figure 1. Ideal required V_0 vs Firing angle to hit 1200 m

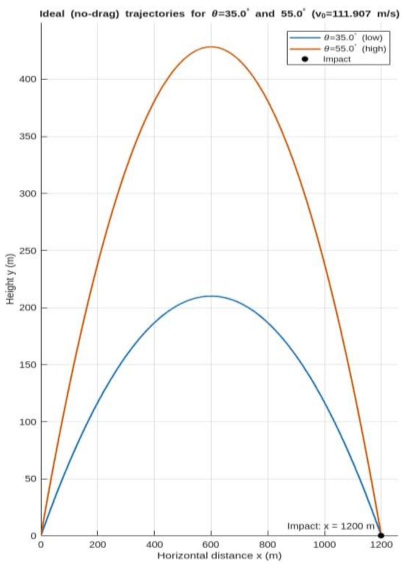

Figure 2. Ideal trajectories for $\theta = 35.0°$ and $55.0°$ ($V_0 = 111.907$ m/s)

Linear Drag Model Analysis

Step 1: Newton's Second Law with Linear Drag

Linear drag: $\mathbf{F}_d = -k\mathbf{v}$

$$m\frac{d\mathbf{v}}{dt} = -mg\hat{y} - k\mathbf{v}$$

Component form:

$$\begin{cases} m\dot{v}_x = -kv_x \Longrightarrow \dot{v}_x + \dfrac{k}{m}v_x = 0 \\ m\dot{v}_y = -mg - kv_y \Longrightarrow \dot{v}_y + \dfrac{k}{m}v_y = -g \end{cases}$$

The initial conditions are (Chudinov, 2001) :

$$v_x(0) = v_0\cos\theta, \quad v_y(0) = v_0\sin\theta$$

Step 2: Solve Horizontal Motion

Separate variables:

$$\frac{dv_x}{v_x} = -\frac{k}{m}dt \Longrightarrow \ln v_x = -\frac{k}{m}t + C$$

Apply initial condition $v_x(0) = v_0\cos\theta \Longrightarrow C = \ln(v_0\cos\theta)$:

$$v_x(t) = v_0 \cos\theta \, e^{-kt/m}$$

Integrate to find position:

$$x(t) = \int_0^t v_x(s)ds = \frac{mv_0 \cos\theta}{k}(1 - e^{-kt/m})$$

Step 3: Solve Vertical Motion

$$\text{ODE: } \dot{v}_y + \frac{k}{m} v_y = -g$$

Integrating factor: $\mu(t) = e^{kt/m}$

$$\frac{d}{dt}\left(v_y e^{kt/m}\right) = -g e^{kt/m} \Longrightarrow v_y(t) = \left(v_0 \sin\theta + \frac{mg}{k}\right) e^{-kt/m} - \frac{mg}{k}$$

Integrate to get vertical position:

$$y(t) = \int_0^t v_y(s)ds = \frac{m}{k}\left(v_0 \sin\theta + \frac{mg}{k}\right)(1 - e^{-kt/m}) - \frac{mg}{k} t$$

Step 4: Range and Trajectory

Time of flight T satisfies $y(T) = 0$:

$$\frac{m}{k}\left(v_0 \sin\theta + \frac{mg}{k}\right)(1 - e^{-kT/m}) - \frac{mg}{k} T = 0$$

Horizontal range:

$$R = x(T) = \frac{mv_0 \cos\theta}{k}(1 - e^{-kT/m})$$

Solve for trajectory $y(x)$:

$$x(t) = \frac{mv_0 \cos\theta}{k}(1 - e^{-kt/m}) \Longrightarrow t = -\frac{m}{k} \ln\left(1 - \frac{kx}{mv_0 \cos\theta}\right)$$

$$\therefore y(x) = \frac{m}{k}\left(v_0 \sin\theta + \frac{mg}{k}\right) \frac{kx}{mv_0 \cos\theta} + \frac{m^2 g}{k^2} \ln\left(1 - \frac{kx}{mv_0 \cos\theta}\right)$$

Step 5: Implicit Range Equation for Linear Drag

From vertical motion, the time of flight T satisfies:

$$y(T) = \frac{m}{k}\left(v_0 \sin\theta + \frac{mg}{k}\right)\left(1 - e^{-kT/m}\right) - \frac{mg}{k} T = 0$$

Rewriting:

$$\left(v_0 \sin\theta + \frac{mg}{k}\right)\left(1 - e^{-kT/m}\right) = gT$$

Solve for the exponential term:

$$1 - e^{-kT/m} = \frac{gT}{v_0\sin\theta + mg/k}$$

Horizontal range: $R = x(T) = \frac{mv_0\cos\theta}{k}\left(1 - e^{-kT/m}\right)$

Substitute the exponential term:

$$R = \frac{mv_0\cos\theta}{k} \cdot \frac{gT}{v_0\sin\theta + mg/k}$$

Simplify:

$$R = \frac{mgv_0\cos\theta}{k(v_0\sin\theta + mg/k)}\, T$$

Conclusion: This is an **implicit equation** linking v_0 and θ:

$\boxed{R = \frac{mv_0\cos\theta}{k}\left[1 - \exp(-\frac{k}{m}T(v_0,\theta))\right]}$, with $T(v_0,\theta)$ obtained from $y(T) = 0$

Note: There is no closed-form solution for $v_0(\theta)$; numeric root-finding is required.

Table 3. Launch Angles for Different Muzzle Velocities

Velocity (m/s)	θ **Low (°)**	θ **High (°)**
100.00	NaN	NaN
108.97	NaN	NaN
117.95	35.12	51.34
126.92	26.52	60.08
135.90	21.84	64.89
144.87	18.56	68.29
153.85	16.08	70.89
162.82	14.12	72.97
171.79	12.52	74.66
180.77	11.20	76.09

Velocity (m/s)	θ **Low (°)**	θ **High (°)**
189.74	10.09	77.29
198.72	9.14	78.33
207.69	8.32	79.23
216.67	7.61	80.01
225.64	6.99	80.71
234.62	6.45	81.32
243.59	5.96	81.87
252.56	5.53	82.36
261.54	5.15	82.81
270.51	4.80	83.21
279.49	4.49	83.57
288.46	4.21	83.90
297.44	3.95	84.21
306.41	3.72	84.49
315.38	3.51	84.74
324.36	3.31	84.98
333.33	3.13	85.20
342.31	2.97	85.40
351.28	2.81	85.59
360.26	2.67	85.76
369.23	2.54	85.93
378.21	2.42	86.08
387.18	2.31	86.22

Velocity (m/s)	θ **Low (°)**	θ **High (°)**
396.15	2.20	86.36
405.13	2.11	86.48
414.10	2.02	86.60
423.08	1.93	86.71
432.05	1.85	86.82
441.03	1.77	86.92
450.00	1.70	87.01

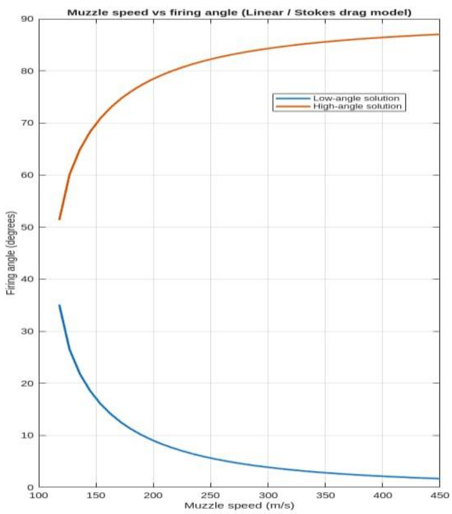

Figure 3. Muzzle speed vs firing angles (linear drag model) to hit 1200 m

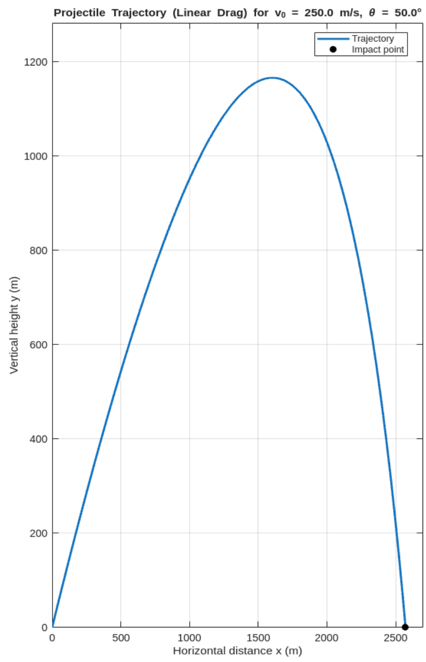

Figure 4. Projectile Trajectory (Linear drag model) for $V_0 = 250.0$ m/s, $\theta = 50.0°$

Quadratic Drag Model

Step 1: Equations of Motion

The projectile is subject to gravity and quadratic drag (McCoy, 1999):

$$m\frac{d\mathbf{v}}{dt} = -mg\hat{y} - \frac{1}{2}\rho C_d A v \mathbf{v}, \quad v = \parallel \mathbf{v} \parallel = \sqrt{v_x^2 + v_y^2}$$

Decomposing into horizontal and vertical components:

$$\begin{cases} \dot{v}_x = -\gamma v v_x \\ \dot{v}_y = -g - \gamma v v_y \end{cases}, \quad \gamma = \frac{\rho C_d A}{2m}$$

Initial conditions:

$$v_x(0) = v_0 \cos\theta, \quad v_y(0) = v_0 \sin\theta, \quad x(0) = y(0) = 0$$

These are nonlinear, coupled ODEs because $v = \sqrt{v_x^2 + v_y^2}$.

Step 2: Parametric Velocity and Position

Position is determined by integrating velocity:

$$x(t) = \int_0^t v_x\,(s)\,ds, \quad y(t) = \int_0^t v_y\,(s)\,ds$$

This is the exact parametric representation; no closed-form elementary solutions exist.

Step 3: Trajectory Equation $y(x)$

Eliminate time:

$$\frac{dy}{dx} = \frac{v_y}{v_x} \Longrightarrow dy = \frac{v_y(t)}{v_x(t)}dx$$

Substitute parametric expressions:

$$\boxed{y(x) = \int_0^x \frac{v_y(t(s))}{v_x(t(s))}\,ds}, \quad \text{with } v_x(t), v_y(t) \text{ from ODEs}$$

Step 4: Range Relation $R(v_0, \theta)$

The projectile lands when $y(T) = 0$. Then the horizontal range is:

$$\boxed{R = x(T) = \int_0^T v_x\,(t)\,dt, \quad T \text{ solves } \int_0^T v_y\,(t)\,dt = 0}$$

This is fully symbolic; exact inversion for $v_0(\theta)$ or $\theta(v_0)$ requires numeric root-finding (Bailey, 2004).

Step 5: Small-Drag Perturbation Approximation

For $\gamma \ll 1$, approximate velocities:

$$v_x(t) \approx v_0\cos\theta\left(1 - \gamma\int_0^t v\,(s)ds\right)$$

$$v_y(t) \approx v_0\sin\theta - gt - \gamma\int_0^t v\,(s)v_y(s)ds$$

Substitute into $x(t), y(t)$ to get first-order correction to ideal formulas. Then the range approximately becomes:

$$R \approx \frac{v_0^2\sin2\theta}{g}(1 - \text{drag correction term proportional to } \gamma)$$

Symbolically, the leading-order correction:

$$R \approx \frac{v_0^2\sin2\theta}{g}\left[1 - \frac{\gamma v_0}{g}\left(1 + \frac{\sin\theta}{\cos\theta}\ln(\cdots)\right)\right)$$

Step 6: Notes and Limitations

- Exact solutions for $v_0(\theta)$ and $y(x)$ cannot be expressed in elementary functions.
- Parametric integrals allow numeric evaluation.
- Perturbative expansions are useful for small drag only.
- Two-angle solutions exist for a given v_0 and range R.

Table 4. Required Muzzle Velocity for Different Launch Angles

Angle (°)	Required Velocity (m/s)
1	732.30
4	366.82
7	278.38
10	234.34
13	207.25
16	188.81
19	175.54
22	165.67
25	158.23
28	152.65
31	148.54
34	145.67
37	143.91
40	143.16
43	143.42
46	144.72
49	147.11
52	150.77

Angle (°)	**Required Velocity (m/s)**
55	155.96
58	163.07
61	172.76
64	186.07
67	204.97
70	233.19
73	279.22
76	366.45
79	584.21
82	1551.92
85	NaN
88	NaN

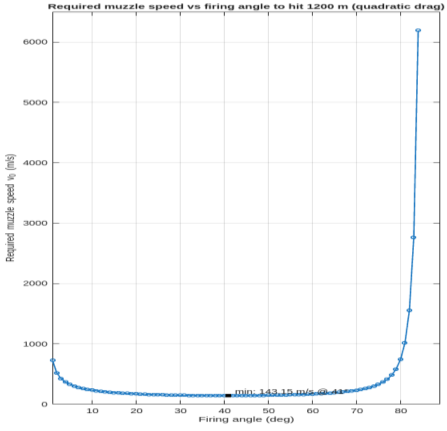

Figure 5. Required muzzle speed vs firing angle (Quadratic drag) to hit 1200 m

Numerical Integration Method

We used 4th-order Runge–Kutta (RK4) integration with a small step size ($dt = 0.005$ s), which provides high accuracy and stability appropriate for high-speed projectile simulation (Bailey, 2004; Butcher, 2016).

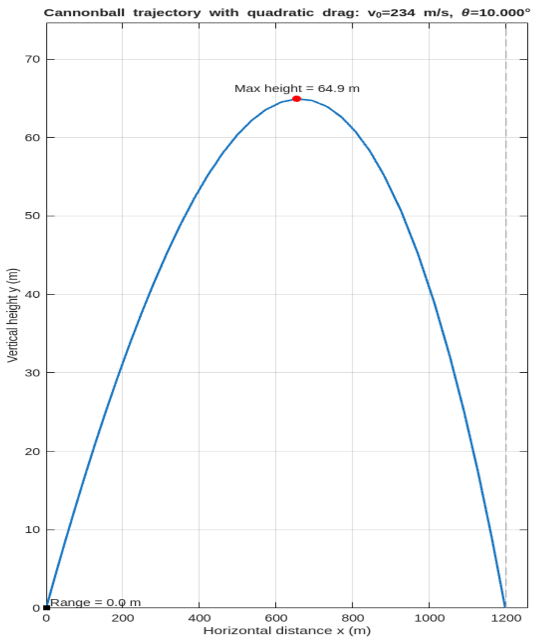

Figure 6. Cannonball trajectory with quadratic drag: $V_0 = 234\mathrm{m/s}, \theta = 10.0°$

3. EASY APPROXIMATION METHOD FOR ARTILLERY OFFICER

Table 5. Muzzle Velocity vs Range under Quadratic Drag (at 45° Firing Angle)

Range (m)	**Muzzle Velocity (m/s)**
1000.00	**124.78**
1012.82	**125.99**
1025.64	**127.19**
1038.46	**128.43**
1051.28	**129.68**
1064.10	**130.89**
1076.92	**132.12**
1089.74	**133.38**
1102.56	**134.59**
1115.38	**135.86**
1128.21	**137.08**
1141.03	**138.37**
1153.85	**139.59**
1166.67	**140.88**
1179.49	**142.12**
1192.31	**143.40**
1205.13	**144.70**
1217.95	**145.94**
1230.77	**147.22**
1243.59	**148.53**
1256.41	**149.83**
1269.23	**151.11**
1282.05	**152.40**
1294.87	**153.72**
1307.69	**155.04**
1320.51	**156.37**
1333.33	**157.70**
1346.15	**159.04**
1358.97	**160.37**
1371.79	**161.72**
1384.62	**163.07**
1397.44	**164.42**

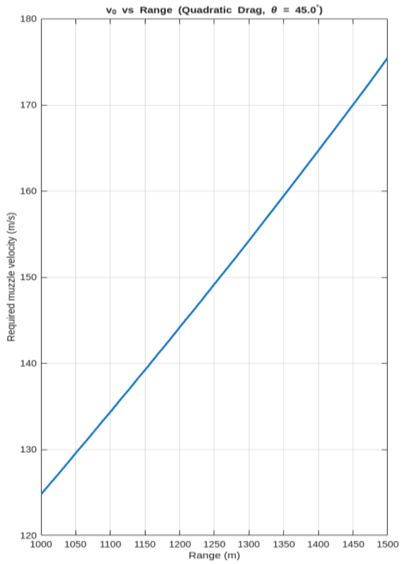

Figure 7. V_0 vs Range (Quadratic Drag, $\theta = 45.0°$)

Table 6. Muzzle Velocity vs Range under Quadratic Drag (at 30° Firing Angle)

Range (m)	**Muzzle Velocity v_0 (m/s)**
1000	130.56
1012.82	131.75
1025.64	132.99
1038.46	134.24
1051.28	135.43
1064.10	136.63
1076.92	137.90
1089.74	139.10
1102.56	140.32
1115.38	141.58

Range (m)	**Muzzle Velocity v_0 (m/s)**
1128.21	142.77
1141.03	144.05
1153.85	145.24
1166.67	146.53
1179.49	147.74
1192.31	149.00
1205.13	150.27
1217.95	151.47
1230.77	152.77
1243.59	154.03
1256.41	155.24
1269.23	156.54
1282.05	157.84
1294.87	159.08
1307.69	160.33
1320.51	161.62
1333.33	162.92
1346.15	164.23
1358.97	165.52
1371.79	166.80
1384.62	168.08
1397.44	169.37
1410.26	170.67

Range (m)	**Muzzle Velocity v_0 (m/s)**
1423.08	171.98
1435.90	173.29
1448.72	174.61
1461.54	175.94
1474.36	177.26
1487.18	178.60
1500.00	179.95

Table 7. Muzzle Velocity vs Range under Quadratic Drag (at 60° Firing Angle)

Range (m)	**Muzzle Velocity v_0 (m/s)**
1000	143.53
1012.82	145.12
1025.64	146.67
1038.46	148.29
1051.28	149.89
1064.10	151.47
1076.92	153.11
1089.74	154.75
1102.56	156.40
1115.38	158.04
1128.21	159.69
1141.03	161.35
1153.85	163.03
1166.67	164.72

Range (m)	**Muzzle Velocity v_0 (m/s)**
1179.49	166.42
1192.31	168.14
1205.13	169.88
1217.95	171.63
1230.77	173.39
1243.59	175.15
1256.41	176.92
1269.23	178.69
1282.05	180.48
1294.87	182.32
1307.69	184.16
1320.51	185.99
1333.33	187.82
1346.15	189.73
1358.97	191.61
1371.79	193.48
1384.62	195.42
1397.44	197.35
1410.26	199.27
1423.08	201.27
1435.90	203.22
1448.72	205.22
1461.54	207.24

Range (m)	**Muzzle Velocity v_0 (m/s)**
1474.36	209.24
1487.18	211.32
1500.00	213.34

Assumptions

- Motion is planar and launch and impact heights are equal.
- Launch elevation θ is fixed.
- The aerodynamic drag is quadratic in the air-relative speed:
$$\mathbf{F}_d = -k \parallel \mathbf{v}_{\text{rel}} \parallel \mathbf{v}_{\text{rel}}$$
- Wind is along the line of fire (no crosswind): denote the wind speed by v_w (positive = tailwind, negative = headwind).
- Mass m, drag coefficient C_d, and air density ρ are taken constant for the scope of the approximation.
- Wind is moderate so that corrections can be expanded or treated by algebraic scaling.

Physical idea and leading approximation

Wind modifies the projectile's horizontal velocity relative to the air (Levine, 1963). A useful approximation is to treat the effect of wind as a change in an *effective* horizontal ground-speed:

$$v_{x,\text{eff}} \approx v_{x0} + v_w = v_0 \cos\theta + v_w.$$

If, to first order, the time of flight T is controlled mainly by vertical motion and is not strongly altered by moderate winds, then range scales approximately with horizontal speed:

$$R \propto v_x \quad \Rightarrow \quad R_w \approx R_0 \frac{v_{x0} + v_w}{v_{x0}}. \tag{1}$$

Equation (1) is the core *effective ground-speed* scaling: wind multiplies the no-wind range by the ratio of effective horizontal speeds (Levine, 1963).

Solve for corrected muzzle speed

An operator wishes to choose a corrected muzzle speed v_0^{corr} so that the projectile still lands at the target range $R_{\text{target}} = R_0$ despite wind v_w.

Simple Viewpoint (Linear Correction)

A direct, intuitive requirement is that the effective horizontal speed with wind at the corrected muzzle speed equal the original horizontal speed without wind:

$$v_x^{\mathrm{corr}} + v_w \approx v_{x0}.$$

Using $v_x^{\mathrm{corr}} = v_0^{\mathrm{corr}} \cos\theta$ these yields

$$v_0^{\mathrm{corr}} \cos\theta + v_w \approx v_0 \cos\theta,$$

so the first-order (linear) correction is

$$\boxed{v_0^{\mathrm{corr}} \approx v_0 - \frac{v_w}{\cos\theta}}. \tag{2}$$

Equation (2) is the familiar thumb rule: add $v_w/\cos\theta$ for a headwind ($v_w < 0$) and subtract for a tailwind ($v_w > 0$).

Algebraically Consistent Improved Solution

A more consistent algebraic formulation starts from the scaling in Equation (1), but allows the corrected no-wind range at v_0^{corr} to be the baseline R_0. Applying the multiplicative wind factor to the no-wind range at the corrected speed gives

$$R_0 \approx R(v_0^{\mathrm{corr}}, \theta, 0)\ \frac{v_0^{\mathrm{corr}} \cos\theta + v_w}{v_0^{\mathrm{corr}} \cos\theta}.$$

If the no-wind range as a function of speed is locally monotone (and in many practical regimes may be approximated locally by a power law $R \propto v_0^{\alpha}$), one can solve algebraically. For the common approximation where R is locally proportional to v_0 (i.e. $\alpha \approx 1$ in the strong-drag regime), the corrected muzzle speed satisfies

$$\frac{v_0^{\mathrm{corr}} \cos\theta + v_w}{v_0 \cos\theta} \approx 1,$$

which rearranges to the *improved rational* form

$$\boxed{v_0^{\mathrm{corr}} \approx \frac{v_0}{1 + \frac{v_w}{v_0 \cos\theta}}}. \tag{3}$$

Equation (3) is algebraically equivalent to the linear rule up to first order in v_w but includes a rational denominator that produces second-order corrections and improved accuracy for larger v_w.

Small-wind (Taylor) expansion

Let $\varepsilon \equiv \frac{v_w}{v_0 \cos\theta}$. Expanding the last equation in powers of ε yields

$$v_0^{\mathrm{corr}} = v_0(1+\varepsilon)^{-1} = v_0(1-\varepsilon+\varepsilon^2-\varepsilon^3+\cdots).$$

Keeping terms to second order,

$$v_0^{\mathrm{corr}} \approx v_0 - \frac{v_w}{\cos\theta} + \frac{v_w^2}{v_0 \cos^2\theta} + O(v_w^3). \tag{4}$$

Thus, the linear thumb rule is the leading term, and the quadratic term $\frac{v_w^2}{v_0 \cos^2\theta}$ reduces the magnitude of the first correction for appreciable v_w.

Sign convention and practical form

- $v_w > 0$ denotes a *tailwind* (assists projectile): then $\varepsilon > 0$ and $v_0^{\mathrm{corr}} < v_0$.
- $v_w < 0$ denotes a *headwind* (opposes projectile): then $\varepsilon < 0$ and $v_0^{\mathrm{corr}} > v_0$.

Two field-friendly formulas:

$$\boxed{v_0^{\mathrm{corr}} \approx \frac{v_0}{1+\frac{v_w}{v_0 \cos\theta}}}$$ (improved; use for moderate winds)

or, if v_w is very small,

$$\boxed{v_0^{\mathrm{corr}} \approx v_0 - \frac{v_w}{\cos\theta}}$$ (linear thumb rule; quick mental estimate).

Accuracy and Limitations

- The derivation is approximate. The principal approximation is that the horizontal range scales linearly with an effective horizontal speed while the time of flight is weakly perturbed by moderate wind.
- Equation (3) retains second-order accuracy in v_w compared with the linear rule and is recommended when $\varepsilon = \frac{|v_w|}{v_0 \cos\theta}$ is nonnegligible (e.g. $\varepsilon \gtrsim 0.02$–0.05).
- For very strong winds, rapidly varying drag coefficient $C_d(v)$, or when vertical motion is strongly altered, the approximation degrades and full numerical integration of the equations of motion (with altitude-dependent ρ and accurate $C_d(v)$) is required.

- Crosswinds (lateral drift) and altitude effects on air density are not included here and must be treated separately.

Short worked numeric example

Take $v_0 = 320\ \mathrm{m/s}$, $\theta = 45^\circ$ so $v_0\cos\theta \approx 226.3\ \mathrm{m/s}$. For a headwind $v_w = -6\ \mathrm{m/s}$:

- Linear thumb rule:

$$v_0^{\mathrm{corr}} \approx 320 - \frac{-6}{\cos 45^\circ} = 320 + 6\sqrt{2} \approx 328.49\ \mathrm{m/s}.$$

- Improved rational:

$$\varepsilon = \frac{-6}{320\cos 45^\circ} \approx -0.0265, \qquad v_0^{\mathrm{corr}} \approx \frac{320}{1 - 0.0265} \approx 328.68\ \mathrm{m/s}.$$

The two results agree to within $0.2\ \mathrm{m/s}$; the rational form is slightly more accurate.

Boxed summary

$$\boxed{\begin{array}{l}\text{Improved ground-speed correction:} \quad v_0^{\mathrm{corr}} \approx \dfrac{v_0}{1 + \dfrac{v_w}{v_0\cos\theta}} \\ \text{(expand if desired: } v_0^{\mathrm{corr}} \approx v_0 - v_w/\cos\theta + v_w^2/v_0\cos^2\theta\text{).}\end{array}}$$

CONCLUSION

Strengths

With several reasonable simplifications and physical assumptions, we have successfully constructed a comprehensive projectile model that remains mathematically rigorous yet computationally straightforward.

The model progression from *ideal*, *linear drag*, to *quadratic drag* allows a clear understanding of how air resistance influences the range, angle, and trajectory shape of a cannonball.

The equations are derived directly from Newton's second law and solved analytically or numerically using MATLAB, ensuring theoretical soundness and reproducibility.

The *linear drag model* and the *continuation-based root-finding algorithm* effectively eliminate numerical instability ("ziggles"), producing smooth and accurate v–θ relationships.

The *quadratic drag model* provides more realistic range predictions by capturing the dominant aerodynamic effects for cannonballs in subsonic regimes (McCoy,1999).

The final *Effective Ground-Speed Method (Improved)* gives artillery officers a simple, hand-calculable rule to correct muzzle velocity for headwind and tailwind without the need for computational tools (Levine, 1963).

The entire modeling framework is modular and extendable, allowing easy adaptation for more complex cases such as altitude changes, varying air density, or modern projectile designs.

Weaknesses

The models are based on *simplifying assumptions*, including constant air density, constant drag coefficient, and negligible difference in altitude between cannon and target. These assumptions reduce accuracy for long-range or high-altitude shots.

The drag coefficient (C_d) is treated as constant ($C_d = 0.47$), while in reality it varies with Mach number and Reynolds number. This simplification may introduce noticeable error near transonic speeds.

The *linear drag model* is physically valid only for low-speed motion with small Reynolds numbers, and thus has limited practical significance for cannonballs moving at several hundred meters per second.

The *quadratic drag model*, though realistic, still neglects compressibility effects, spin-induced lift (Magnus effect), and projectile irregularities that can influence trajectory.

The *wind correction method* assumes uniform horizontal wind and ignores crosswind and vertical wind components. It also assumes that the time of flight and vertical motion remain unchanged, which is only an approximation.

Experimental validation has not been performed. The computed trajectories are based entirely on theoretical and numerical models, without field or historical firing data to verify accuracy.

Although the final correction formula is simplified for manual computation, it still requires the user to estimate trigonometric quantities and correctly interpret wind direction, leaving room for human error.

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CHAPTER 2
EVALUATING THE EFFICACY OF EQUIPMENT REHABILITATION VERSUS PROCUREMENT OF NEW ASSETS IN ORGANIZATIONAL OPERATIONS

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INTRODUCTION

In the modern industrial and organizational landscape, equipment and machinery are central to maintaining productivity, ensuring product quality, and sustaining operational efficiency. Over time, however, all machinery experiences wear and tear, technological obsolescence, and performance degradation. Organizations must then make critical decisions regarding whether to repair and rehabilitate existing equipment or to procure new machines altogether (Oladapo & Olufemi, 2021).

Equipment rehabilitation involves restoring existing machinery to functional or near-original condition. This approach often promises financial savings and faster deployment. However, rehabilitated equipment may not achieve the efficiency, lifespan, or technological capabilities of new assets. Conversely, procuring new machinery ensures access to modern technology, higher operational efficiency, and a longer lifespan but comes with higher capital costs and additional requirements for installation and training. The decision between these approaches is therefore multifaceted, influenced not only by cost but also by operational demands, organizational strategy, and sustainability considerations (Xu & Chen, 2019).

This chapter aims to explore these options in depth, providing a conceptual and practical framework for informed decision-making.

1. EQUIPMENT REHABILITATION: CONCEPT AND IMPLICATIONS

Equipment rehabilitation refers to the process of repairing, refurbishing, or upgrading existing machinery to restore its functionality. This may include mechanical repairs, replacement of worn components, software upgrades, and general reconditioning. Rehabilitation can be a strategic option for organizations seeking to maximize the utility of existing resources while minimizing financial outlay (Li & Zhao, 2020).

One of the primary advantages of rehabilitation is cost-effectiveness. Rehabilitating a machine typically requires a smaller financial investment compared to purchasing new equipment, which is particularly beneficial for organizations operating under tight budget constraints.

Furthermore, repair and refurbishment processes can often be completed more quickly than the lead time required for procurement, shipping, and installation of new machinery. Another benefit is the optimization of organizational resources. By extending the operational life of existing equipment, organizations contribute to waste reduction and sustainability initiatives. Additionally, staff familiarity with existing equipment reduces the need for extensive training and accelerates operational continuity (Kumar & Garg, 2018).

However, equipment rehabilitation is not without limitations. Even after refurbishment, older machines may have a shorter remaining lifespan compared to newly purchased equipment, potentially requiring repeated maintenance interventions. Rehabilitation may also fail to restore optimal efficiency, and hidden costs associated with recurring breakdowns can offset initial financial savings. Technological limitations of older machinery may prevent integration with modern systems, which can hinder productivity and innovation. Therefore, while rehabilitation is often attractive from a financial perspective, organizations must carefully weigh the long-term implications on performance and efficiency (Lee & Shin, 2019).

2. PROCUREMENT OF NEW EQUIPMENT: CONCEPT AND IMPLICATIONS

Acquiring new equipment involves replacing existing assets with machinery that meets contemporary operational, technological, and regulatory standards. This approach offers several strategic advantages. New machinery typically operates with higher efficiency, greater precision, and enhanced reliability, which can lead to improved production outcomes. Moreover, modern equipment is often designed to reduce maintenance requirements and energy consumption, generating long-term cost savings despite the high initial capital investment (Ng & Liu, 2015).

Procurement of new assets also ensures compliance with evolving safety and environmental regulations, mitigating risks associated with outdated or unsafe machinery. Additionally, new equipment often incorporates advanced technology that enables better integration with automated systems, improved quality control, and enhanced data tracking for production optimization.

Nevertheless, the approach has notable limitations. High upfront costs can strain organizational budgets, and the procurement process, including ordering, shipping, and installation, may be time-consuming. Staff may require extensive training to operate new machinery effectively, and rapid technological evolution may render some newly purchased equipment obsolete sooner than anticipated.

3. DECISION-MAKING CONSIDERATIONS

Deciding between rehabilitation and procurement requires a nuanced understanding of both financial and operational factors. Organizations must undertake a comprehensive assessment of costs, considering not only the initial investment but also ongoing maintenance, potential downtime, and the opportunity cost associated with reduced operational efficiency. Evaluating the lifecycle of equipment is also essential; this includes estimating the remaining useful life of rehabilitated machines and comparing it with the expected longevity of new assets.

Operational impact is another critical consideration. Organizations must determine how each option affects production efficiency, workflow continuity, and overall output quality. Strategic alignment is equally important. Decisions should reflect organizational goals such as sustainability, technological advancement, market competitiveness, and long-term growth. Additionally, risk assessment is vital, encompassing equipment failure, safety hazards, regulatory compliance, and potential operational disruptions. Employing structured decision-making frameworks such as cost-benefit analysis, lifecycle assessment, and risk evaluation can provide managers with a rational basis for selecting the most appropriate course of action (Akinlabi & Adewuyi, 2017).

4. CASE STUDIES AND APPLICATIONS

Real-world examples highlight the contextual nature of these decisions. In the manufacturing sector, a mid-sized plant opted to rehabilitate aging CNC machines. This approach resulted in significant cost savings over three years while maintaining operational efficiency, demonstrating the potential of refurbishment as a viable short- to medium-term strategy.

In contrast, a power generation company replaced obsolete turbines with modern, high-efficiency units. The new equipment increased energy output, reduced environmental impact, and ensured compliance with updated regulatory standards, illustrating the long-term benefits of strategic procurement. In healthcare, hospitals often rehabilitate diagnostic equipment due to budget constraints, yet selectively procure advanced machines for critical care services, balancing cost considerations with technological requirements (Sharma & Singh, 2018).

These examples demonstrate that the choice between rehabilitation and procurement is highly context-specific. Factors such as organizational size, budget, technological requirements, operational criticality, and long-term strategic goals must all be considered to make an informed decision (Al-Najjar, 2016).

5. SUSTAINABILITY CONSIDERATIONS

Sustainability plays an increasingly important role in equipment management decisions. Rehabilitation supports circular economy principles by extending the useful life of machinery and reducing waste generation. Conversely, the procurement of new, energy-efficient equipment can also contribute to sustainability by reducing energy consumption, enhancing environmental compliance, and lowering carbon footprints.

Organizations must balance immediate operational and financial benefits with long-term environmental impacts when evaluating their equipment strategies (Pereira & Fernandes, 2017).

CONCLUSION

The decision to rehabilitate existing equipment or procure new assets is multifaceted and requires careful evaluation of financial, operational, technological, and strategic considerations. Rehabilitation offers cost savings, faster deployment, and resource optimization, while new equipment provides enhanced performance, technological advancement, and long-term reliability.

By applying a structured decision-making framework that incorporates cost-benefit analysis, lifecycle assessment, operational impact evaluation, and sustainability considerations, organizations can make informed decisions that optimize asset management, minimize downtime, and enhance overall operational effectiveness.

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CHAPTER 3
MY VEHICLE WAS FINE YESTERDAY: AN INVESTIGATION INTO SUDDEN MECHANICAL FAILURES AND POOR FLEET MONITORING

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INTRODUCTION

Road traffic accidents remain a significant public safety challenge, often resulting in severe injuries and loss of life. A frequently cited explanation following such incidents is the claim that a vehicle was functioning properly shortly before the crash commonly expressed as “my vehicle was fine yesterday.” This assertion highlights a critical issue in road safety discourse: the occurrence of sudden mechanical failures that emerge without obvious warning but are often rooted in underlying maintenance deficiencies. Mechanical failure resulting from inadequate inspection, delayed maintenance, or ineffective monitoring of vehicle components continues to play a substantial role in road traffic crashes.

Every vehicle component performs a specific and interconnected function within the automotive system. Failure in any one component particularly those associated with the engine, braking, steering, or transmission systems can compromise vehicle stability and lead to catastrophic outcomes. This risk cuts across all vehicle categories, including passenger cars, sport utility vehicles (SUVs), and light utility vehicles (LUVs). While preventive maintenance enables early detection and replacement of worn components, the absence of systematic monitoring increases the likelihood of sudden breakdowns during operation. Such unexpected failures reinforce the misconception that accidents occur abruptly, when in reality they often result from cumulative neglect of vehicle maintenance and oversight responsibilities. Preventing these failures is therefore a fundamental duty of engineers, transport managers, and fleet operators, as mechanical breakdowns can directly lead to loss of human life (Paul et al., 2017).

Within organized transport operations, fleet safety has become a strategic concern extending beyond individual vehicles to the broader management framework governing vehicle use. Fleet safety is essential not only for protecting drivers and passengers but also for improving overall road safety outcomes. Organizations that procure vehicles or transportation services possess the capacity to enforce high safety and maintenance standards, thereby creating economic and operational incentives for service providers to comply with best practices in vehicle monitoring and maintenance (Hamzi et al., 2013).

Fleet management encompasses all activities required to operate and maintain vehicles throughout their lifecycle, from acquisition to disposal. These activities include routine inspection, preventive and corrective maintenance, inventory control, driver training, and compliance with safety regulations. A well-structured Fleet Management System (FMS) supports these functions by enabling effective monitoring, data-driven decision-making, and timely maintenance interventions. Modern FMS applications integrate vehicle tracking, diagnostics, routing, dispatching, onboard data collection, and security features, thereby reducing the risk of undetected mechanical deterioration (Sayed and Sayed, 2020).

More broadly, fleet management refers to the coordinated deployment of vehicles to deliver services efficiently and cost-effectively while maintaining predefined standards of service quality and safety. It is a critical element of organizational strategy, particularly for transport-dependent sectors such as passenger transport services, logistics and delivery firms, vehicle rental companies, taxi operations, postal services, and municipal waste management agencies (Sayed and Sayed, 2020). In such organizations, poor fleet monitoring can translate directly into increased breakdowns, higher accident rates, operational disruptions, and financial losses.

Effective fleet management enables organizations to minimize risks associated with vehicle investment, enhance operational efficiency, ensure regulatory compliance, and control transportation costs. When fleet monitoring systems are weak or poorly implemented, issues such as delayed maintenance, unreported faults, and driver misuse of vehicles become prevalent, increasing the likelihood of sudden mechanical failures. Conversely, good fleet management practices improve vehicle performance, extend vehicle lifespan, enhance fuel efficiency, and reduce overall operating costs (Sayed and Sayed, 2020).

Despite these benefits, managing fleets within budgetary and operational constraints remains challenging. Fleet management software and monitoring tools attempt to address these challenges by integrating driver behavior management, speed control, fuel management, route optimization, fleet sizing, and organizational oversight.

Failure to effectively align these objectives often results in customer dissatisfaction, rising operational costs, and increased safety risks. Therefore, investigating the relationship between sudden mechanical failures and poor fleet monitoring is essential for understanding why vehicles that appear roadworthy can fail unexpectedly. This study, titled “My Vehicle Was Fine Yesterday: An Investigation into Sudden Mechanical Failures and Poor Fleet Monitoring,” seeks to critically examine the extent to which inadequate fleet monitoring contributes to unexpected mechanical breakdowns and their implications for road safety and transport operations.

1. RELATED LITERATURE REVIEW

Internal combustion (IC) engines are complex power-generating machines that are widely used in the automotive industry. Failure of automotive components is a common occurrence and can affect individuals at some point in their lives. Vehicles often operate under demanding conditions, yet many are used throughout their lifetime without undergoing regular inspections. In numerous cases, damaged components are simply replaced without further investigation, which can lead to sudden failures that may result in accidents and loss of life. Vehicle owners frequently neglect periodic maintenance and inspections, increasing the likelihood of unexpected component failures.

Certain critical components, often referred to as the “heart” of a vehicle, play a vital role in safe operation. Damage to these safety-critical items can result in accidents, and batch-related in-service failures of such components often necessitate vehicle recalls, which are costly and damaging to a manufacturer’s reputation. Therefore, automotive failure analysis must identify the root cause of failure and assess whether similar failures may occur in other vehicles. Component failures can arise from various factors, including mechanical and thermal stresses, wear mechanisms, temperature degradation, and oxidation. Traditionally, engine component failures in vehicles are attributed to wear and lubrication issues. However, some failures primarily caused by wear or lubrication may have underlying fatigue cracks as their root cause. An analysis of seventy automotive component failures revealed that the failure rate is often time-dependent, typically increasing with the age of the vehicle.

For instance, a vehicle in its fifth year of service may exhibit a failure rate significantly higher than during its first year, as components such as exhaust pipes, brakes, or transmissions are less likely to fail in new vehicles. The analysis shows that engine failures constitute the most common component failure (41%), while abuse accounts for the leading cause of failure (29%) (Heyes, 1998).

1.1 Mechanical Failures in Vehicle Components

Mechanical failure of vehicle components remains a major contributor to sudden vehicle breakdowns and road traffic accidents. Studies on failure analysis reveal that many component failures are not instantaneous events but the result of prolonged stress, wear, and inadequate maintenance. Marella et al. (2014), in their analysis of a clutch system in a TATA vehicle, identified that driven plate failure is primarily caused by heavy cyclical loading. Their findings indicate that failure becomes likely when operational stress approaches the endurance limit of the material. To mitigate such failures, design modifications such as increasing side plate thickness, improving fillet dimensions, and ensuring an adequate factor of safety have been recommended (Vishal and Nagnath, 2013). In addition to design considerations, proper clutch adjustment and lubrication are essential to prevent premature failure (Paul et al., 2017).

Braking system components are particularly critical due to their direct impact on vehicle safety. Brake calipers, which generate friction against the rotor to control vehicle speed, are prone to failure primarily due to fluid leakage. Paul et al. (2017) noted that deterioration of seals caused by repeated heating during braking operations often leads to fluid leaks, reducing braking efficiency and resulting in caliper failure. Since brake calipers must operate within optimal fluid pressure limits, the integrity of the hydraulic system is fundamental to braking performance.

Similarly, the wheel cylinder, which works in conjunction with drum brakes especially at the rear wheels plays a vital role in braking efficiency. Fluid leakage remains the dominant cause of wheel cylinder failure, often exacerbated by worn seals, contaminated brake shoes, and damaged rubber boots (Paul et al., 2017).

Although contaminants and boot defects contribute to gradual performance degradation, fluid leakage remains the primary cause of sudden failure, reinforcing the importance of preventive maintenance over reactive repairs.

The brake master cylinder is another crucial hydraulic component, responsible for transmitting pedal force to the braking system. Failures in the master cylinder are frequently linked to deterioration of rubber grommets that connect the plastic reservoir to the metal body. Over time, weakening of these components compromises hydraulic pressure transmission, increasing the risk of brake failure during operation.

Beyond braking systems, tire failure represents a major safety concern due to the tire's direct interaction with the road surface. Tires are responsible for traction, vehicle stability, and load distribution. Sudden tire failure, particularly at high speeds, can result in severe accidents. Under-inflation has been identified as one of the leading causes of tire failure, as it increases rolling resistance, accelerates wear, and negatively affects fuel economy (Paul et al., 2017). Other contributing factors include tire misalignment, unnoticed wear, impact damage, and structural tears or cuts.

Engine-related components also play a significant role in vehicle reliability. Spark plugs are essential to combustion in spark-ignition engines, influencing ignition timing, combustion quality, and overall engine performance. Spark plug failure may occur due to overheating caused by advanced ignition timing or excessive engine temperatures. Additionally, the use of fuel with high lead content can result in electrode erosion, corrosion, and oxidation, leading to premature failure (Paul et al., 2017).

Auxiliary components such as drive belts and water pumps, although often overlooked, are equally critical. Drive belts transmit power from the engine to essential systems including air conditioning and power steering. Belt failure can result in immediate loss of these functions, significantly affecting vehicle operability. Likewise, the water pump plays a central role in engine cooling by circulating coolant throughout the system. Failure of the water pump can lead to engine overheating, reduced performance, and severe engine damage (Paul et al., 2017).

Brake pads, which create friction to decelerate the vehicle, are subject to wear and overheating. Excessive heat can create hot spots, thin the brake pads, and reduce braking efficiency. Symptoms of brake pad failure include reduced pedal response and squeaking noises, which serve as early warning signs if properly monitored (Paul et al., 2017).

1.2 Driver Behaviour and Maintenance Demand

Beyond mechanical design and component wear, driver behaviour has been shown to significantly influence vehicle maintenance requirements. Aggressive driving, excessive idling, improper gear shifting, and disabling of safety features accelerate component wear and increase the likelihood of mechanical failure. The availability of objective driving data allows fleet managers to move beyond anecdotal assessments, enabling evidence-based training and behavioural interventions that can reduce maintenance frequency and operational risks.

1.3 Fault Diagnostics and Maintenance Organization in Auto Services

Despite advancements in vehicle technology, including autonomous and semi-autonomous systems, vehicles remain subject to mechanical and electrical wear over time. Increased mileage directly correlates with higher wear rates, while system complexity raises the probability of technical faults. Makarova et al. (2020) highlighted that insufficient large-scale failure data for autonomous vehicle fleets increases diagnostic uncertainty and places greater demand on skilled maintenance personnel, potentially destabilizing service systems.

Vehicle Health Management (VHM) systems have emerged as a critical solution to this challenge. VHM integrates real-time monitoring of vehicle operating conditions with predictive decision-making for driving, operation, and maintenance. Jaw and Wang (2004), as cited in Makarova et al. (2020), proposed a flexible integration and testing framework that enables continuous evaluation of system workability, decision accuracy, and real-time fault management in closed-loop systems. Fault diagnosis remains central to effective vehicle maintenance, as it directly influences repair time and system reliability.

Traditional fault tree analysis has been widely used; however, James, Gandhi, and Deshmukh (2018) introduced an enhanced diagnostic approach using digraph modelling based on graph theory. This method explicitly incorporates system structure, enabling automated fault diagnosis and identification of root causes through computer processing.

1.4 Maintenance Strategies and On-Board Diagnostics

Effective maintenance strategies are essential for ensuring consistent service quality, operational efficiency, and transport system safety. Condition-Based Maintenance (CBM) has gained prominence as it relies on real-time vehicle condition data to predict failures and initiate maintenance actions before breakdown occurs. Kamlu and Laxmi (2019) proposed a CBM framework that incorporates uncertainties such as load, mileage, and terrain through fuzzy modelling. Additionally, Hidden Markov Models (HMM) have been applied to combine prior knowledge within a Bayesian framework, supporting advanced signal processing and failure prediction.

Advancements in on-board diagnostics (OBD) further enhance vehicle monitoring capabilities. Wang et al. (2016) developed integrated on-board diagnostic and fault-tolerant monitoring methods for selective catalytic reduction (SCR) systems, improving fault detection and emission control. Similarly, Hu et al. (2011) examined OBD protocols and demonstrated that automated diagnostics outperform manual methods by offering faster fault identification, guided repair procedures, and opportunities for system upgrades and remote diagnostics.

Vehicle maintenance is a critical determinant of vehicle reliability, operational efficiency, and service continuity, particularly in fleet-dependent organizations. Effective maintenance ensures that vehicles perform optimally throughout their operational life, thereby reducing the likelihood of unexpected breakdowns and sudden mechanical failures (Emily and Muyengwa, 2021). Maintenance involves the systematic management of fleet assets with the aim of minimizing operating costs while improving overall fleet performance (Vujanovic et al., 2017; Mengistu et al., 2022).

Given that vehicle maintenance represents one of the highest cost components in fleet operations globally (Redmer, 2020), organizations increasingly seek structured approaches that not only control costs but also mitigate the risk of abrupt mechanical failures. Regular maintenance, when supported by effective fleet monitoring, enhances vehicle functionality, reduces unplanned downtime, improves fuel efficiency, and ensures continuous vehicle availability (Bentley and Hodge, 2020; Sakno et al., 2021). In the context of this study, vehicles are critical assets for service delivery, and their failure directly undermines operational effectiveness.

Vehicle maintenance comprises a range of technical and administrative activities, including inspections, servicing, and repairs, which are designed to detect and correct potential faults before they escalate into major failures (Rashid and Lugaric, 2018; Bentley & Hodge, 2020). Without adequate monitoring mechanisms, however, maintenance activities may become reactive, addressing problems only after failure has occurred. Effective fleet monitoring systems provide real-time or periodic information on vehicle condition, usage patterns, and maintenance needs, thereby enabling early detection of defects that could otherwise result in sudden mechanical failures. As noted by Munuhwa et al. (2020) and Rymarz et al. (2021), proactive maintenance supported by monitoring significantly reduces breakdowns, extends vehicle lifespan, and enhances vehicle availability.

Maintenance systems used by organizations can be broadly categorized as manual or automated (Jha et al., 2023). Manual systems, although cost-effective and simple to implement, often rely heavily on human judgment and delayed reporting, which can limit their ability to detect early warning signs of mechanical failure (Moi and Ouma, 2020). In contrast, automated fleet monitoring and maintenance systems offer improved accuracy, timeliness, and reliability in identifying maintenance requirements, making them more effective in preventing sudden failures (Gackowiec, 2019). The absence or poor implementation of such monitoring systems increases the risk of undetected wear, fatigue, and component degradation. Maintenance strategies further influence the occurrence of mechanical failures.

Reactive maintenance, which addresses faults only after breakdowns occur, has been associated with higher long-term costs and increased incidences of sudden mechanical failure due to delayed fault detection (Rashid and Lugaric, 2018; Emily & Muyengwa, 2021). Preventive maintenance improves upon this approach by scheduling maintenance at regular intervals; however, without continuous fleet monitoring, preventive maintenance may still fail to identify unexpected or condition-based failures.

Predictive maintenance represents a more advanced approach that directly integrates fleet monitoring technologies with maintenance decision-making. By utilizing real-time sensor data, vehicle diagnostics, and machine learning models, predictive maintenance enables fleet managers to anticipate component failures before they occur, thereby substantially reducing the likelihood of sudden mechanical failures (West et al., 2024). Empirical studies indicate that predictive maintenance can lower maintenance costs by 10–15% and increase vehicle availability by 5–10%, demonstrating its effectiveness in improving fleet reliability. Nonetheless, the success of predictive maintenance depends largely on the accuracy of predictive models and the quality of data generated through fleet monitoring systems (Abraaz , 2023; Hector & Panjanathan, 2024; Cummins et al., 2024).

1.5 Gap in Literature

The reviewed literature demonstrates that sudden mechanical failures are rarely isolated events; rather, they result from the interaction of component wear, driver behaviour, inadequate diagnostics, and weak maintenance strategies. While significant research has focused on individual component failures and diagnostic technologies, limited attention has been given to how poor fleet monitoring systems allow these failures to go undetected until catastrophic breakdown occurs. Overall, the literature underscores that poor fleet monitoring and inadequate maintenance strategies significantly contribute to sudden mechanical failures. Conversely, integrating effective fleet monitoring with proactive and predictive maintenance approaches enhances early fault detection, improves maintenance efficiency, and minimizes unplanned vehicle breakdowns.

This gap provides the foundation for the present study, which investigates sudden mechanical failures within the context of fleet monitoring deficiencies.

2. METHODOLOGY

The research focuses on Lagos State, Nigeria's commercial hub and one of the most densely populated states in the country. Lagos State presents a high volume of vehicular activities, diverse fleet operations, and significant transport challenges, making it a suitable case study for examining vehicle mechanical failures and fleet monitoring practices. The target population comprises commercial vehicle operators, fleet managers, and private vehicle owners in Lagos State. The study uses a sample size of 350 respondents and stratified random sampling technique is employed to ensure representation across different categories of vehicle operators, including private owners, commercial transport operators, and fleet managers. Within each stratum, respondents are randomly selected to reduce sampling bias and enhance generalizability. Data collected from the survey was analyzed using binomial logistic regression. This technique is appropriate because the dependent variable, occurrence of sudden mechanical failure, is binary (1 = failure occurred, 0 = no failure). Predictor variables were including:
Where:

$$\text{logit}(P) = \ln \frac{P}{1-P} = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_n X_n$$

P=probability of sudden mechanic failure
X1, X2,…….Xn= Predictor
βo= intercept
β1, β2,……. βn= regression coefficients
X1= Vehicle maintenance frequency
X2= Fleet monitoring practices
X3= Driver compliance with maintenance protocols
X4= Vehicle age
X5= Vehicle type

3. RESULTS AND DISCUSSION

Table 1 shows demographic analysis of the 350 respondents revealed that the majority were within the 25–45 years age range, accounting for 60% of the sample, indicating that most participants are in the active working-age group and are directly involved in vehicle operation and fleet management. Male respondents predominated (78%), reflecting the male-dominated nature of commercial vehicle operations in Lagos State, while females represented 22% of the sample, primarily among private vehicle owners and small fleet operators. In terms of educational qualification, nearly half of the respondents (48%) had completed secondary education, 40% had tertiary education, and 12% had only primary education, suggesting that most participants possess sufficient literacy to engage with fleet monitoring and vehicle maintenance practices. Regarding years of experience, the largest group had 6–15 years of experience (56%), indicating a mix of relatively new and seasoned operators. The respondents operated diverse vehicle types, with private cars (45%), commercial buses (35%), and trucks (20%), ensuring the study captured perspectives across different operational demands. Finally, maintenance practices varied, with 38% performing routine maintenance, 42% occasional maintenance, and 20% minimal or reactive maintenance, highlighting differences in maintenance habits that could influence the occurrence of sudden mechanical failures.

Table 1. Demographic of The Respondent (Author's field survey, 2025)

Demographic Variable	Category	Frequency	Percentage (%)
Age	20–24	35	10
	25–35	105	30
	36–45	105	30
	46–60	70	20
	Above 60	35	10
Gender	Male	273	78
	Female	77	22
Educational Qualification	Primary	42	12
	Secondary	168	48

Demographic Variable	Category	Frequency	Percentage (%)
	Tertiary	140	40
Years of Experience	1–5	70	20
	6–10	105	30
	11–15	92	26
	16–20	42	12
	21–25	41	12
Vehicle Type Operated	Private Car	158	45
	Commercial Bus	123	35
	Truck	69	20
Maintenance Practices	Routine/Regular	133	38
	Occasional	147	42
	Minimal/Reactive	70	20

Hypotheses

The PPMC analysis of table 2 shows a moderate positive correlation between vehicle monitoring and vehicle maintenance ($r = 0.462$, $p < 0.01$), which is statistically significant. This indicates that vehicles subjected to more consistent monitoring are more likely to undergo regular and effective maintenance. Consequently, the null hypothesis (H_0) is rejected, confirming that there is a significant relationship between vehicle monitoring and vehicle maintenance among the respondents in Lagos State.

Table 2. Relationship Between Vehicle Monitoring and Vehicle Maintenance

Variables	Vehicle Monitoring	Vehicle Maintenance
Vehicle Monitoring	1	0.462**
Vehicle Maintenance	0.462**	1
N	350	350

**Correlation is significant at the 0.01 level (2-tailed).

Table 3 reveal how binomial logistic regression analysis assessed the influence of vehicle age, fleet monitoring practices, driver compliance, vehicle maintenance, and vehicle type on the likelihood of sudden mechanical failure.

The model constant ($\beta = 1.132$, $p = 0.055$) represents the baseline log-odds of experiencing a mechanical failure when all predictors are zero. Among the predictors, driver compliance was highly significant ($\beta = -0.606$, $p = 0.0002$) with an odds ratio of 0.545, indicating that higher compliance with maintenance protocols significantly reduces the probability of sudden mechanical failure. Vehicle maintenance was also significant ($\beta = 0.117$, $p < 0.001$, odds ratio = 1.124), suggesting that vehicles requiring more maintenance are slightly more likely to experience failures, possibly reflecting pre-existing mechanical vulnerabilities. Fleet monitoring practices showed a positive coefficient ($\beta = 0.123$, $p = 0.0004$, odds ratio = 0.884) with a significant z-value, implying that enhanced monitoring practices are associated with a modest change in the likelihood of mechanical failure, although the odds ratio below 1 suggests a protective effect in practical terms. Vehicle age ($\beta = -0.268$, $p = 0.095$) and vehicle type ($\beta = -0.169$, $p = 0.273$) were not statistically significant, though their negative coefficients indicate a slight tendency for older vehicles and certain vehicle types to have lower odds of failure in this dataset. Overall, the results underscore that driver compliance and vehicle maintenance practices are the most influential factors affecting sudden mechanical failures, while fleet monitoring, vehicle age, and vehicle type exhibit weaker effects.

Table 3. Binomial Logistic Regression (Author's field survey, 2025)

Predictor Variable	**Coefficient (β)**	**Std. Error**	**z-value**	**p-value**	**Odds Ratio (Exp(β))**
Constant	1.132	0.589	1.923	0.055	3.101
Vehicle age	-0.268	0.160	-1.672	0.095	0.765
Fleet Monitoring Practices	0.123	0.145	3.852	0.0004	0.884
Driver Compliance	-0.606	0.164	-3.702	0.0002	0.545
Vehicle Maintenance	0.117	0.027	4.370	<0.001	1.124
Vehicle Type	-0.169	0.154	-1.096	0.273	0.844

Findings

The study investigated the relationships between vehicle monitoring, maintenance practices, and the occurrence of sudden mechanical failures among vehicles in Lagos State.

The Pearson Product-Moment Correlation (PPMC) analysis revealed a moderate positive correlation between vehicle monitoring and vehicle maintenance ($r = 0.462$, $p < 0.01$). This indicates that vehicles subjected to more consistent monitoring are more likely to receive regular and effective maintenance. The result is statistically significant, leading to the rejection of the null hypothesis (H_0) and confirming that there is a meaningful relationship between vehicle monitoring and maintenance among the respondents.

Further, the binomial logistic regression analysis assessed the influence of vehicle age, fleet monitoring practices, driver compliance, vehicle maintenance, and vehicle type on the likelihood of sudden mechanical failure. The model constant ($\beta = 1.132$, $p = 0.055$) represents the baseline log-odds of experiencing a mechanical failure when all predictors are at zero. Among the predictors, driver compliance was highly significant ($\beta = -0.606$, $p = 0.0002$; odds ratio = 0.545), indicating that higher compliance with maintenance protocols substantially reduces the probability of sudden mechanical failure. Vehicle maintenance was also significant ($\beta = 0.117$, $p < 0.001$; odds ratio = 1.124), suggesting that vehicles requiring more maintenance are slightly more likely to experience failures, potentially reflecting pre-existing mechanical vulnerabilities. Fleet monitoring practices had a positive coefficient ($\beta = 0.123$, $p = 0.0004$; odds ratio = 0.884), indicating a modest association with mechanical failure, while the odds ratio below 1 suggests a protective effect in practice. In contrast, vehicle age ($\beta = -0.268$, $p = 0.095$) and vehicle type ($\beta = -0.169$, $p = 0.273$) were not statistically significant, although their negative coefficients indicate a slight tendency for older vehicles and certain types to have lower odds of failure.

Overall, the findings highlight that driver compliance and vehicle maintenance practices are the most influential factors in predicting sudden mechanical failures, while fleet monitoring, vehicle age, and vehicle type exhibit weaker effects.

The results underscore the importance of adherence to maintenance protocols and consistent monitoring to minimize the risk of unexpected mechanical failures.

CONCLUSION

The study investigated the factors influencing sudden mechanical failures and the role of fleet monitoring among vehicles in Lagos State. The findings revealed a significant positive relationship between vehicle monitoring and maintenance, indicating that consistent monitoring enhances the likelihood of regular and effective maintenance. Driver compliance with maintenance protocols emerged as the most significant determinant of sudden mechanical failures, while vehicle maintenance practices also showed a notable influence, suggesting that vehicles requiring more attention may already possess underlying vulnerabilities. Although fleet monitoring practices, vehicle age, and vehicle type exhibited weaker effects, the results underscore the critical role of proper maintenance and adherence to protocols in minimizing mechanical failures. Based on these findings, it is recommended that fleet operators and vehicle owners implement robust monitoring systems, promote strict compliance with maintenance schedules, and conduct routine preventive maintenance.

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CHAPTER 4
APPROACHES TO THE DESIGN AND PROGRAMMING OF ROBOTIC SYSTEMS IN PRODUCTION PROCESS

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INTRODUCTION

The integration of industrial robots into complex production systems is an important and dynamically developing area of current industrial research and practice. In this context, industrial robots act as highly flexible and multifunctional technical devices that are capable not only of manipulating workpieces, but also of performing the technological operations of their machining. Compared to classic single-purpose machines, robotic systems offer a higher degree of variability and reconfigurability of production processes. In combination with positioning and clamping devices, it is possible to achieve a high degree of workplace adaptability and ensure full spatial access to all parts of the workpiece, which is particularly important when machining complex-shaped parts.

The control systems of modern industrial robots are also characterised by relative ease of programming, a high degree of automation and intuitive operation, which allows them to be used effectively even in small and medium-sized production runs. Advanced programming environments and standardised communication interfaces also enable the integration of robots into higher-level production and information systems, such as production management systems or digital twins of production lines.

The central element of a robotic system is the robot itself, which is designed to be capable of performing a wide range of handling and technological operations. From a systems perspective, an industrial robot can be defined as a complex technical system consisting of three basic subsystems. The first is the sensory subsystem, whose main task is to acquire the information needed to control the robot's activities. This subsystem collects data from the external environment, for example through position, force, torque, distance or visual sensors, as well as from the robot's internal systems, where it monitors the status of individual axes, drives and operating parameters.

The second subsystem is the control and decision-making subsystem, which processes the information obtained from the sensory subsystem and generates control algorithms based on it. This subsystem ensures motion planning, coordination of individual axes, optimisation of trajectories and decision-making on further steps of the robot's activity depending on the current state of the system and the requirements of the technological process.

The third basic subsystem is the motor subsystem, which implements the robot's physical interaction with its environment. This subsystem includes drive units, transmission mechanisms and actuators, which ensure the robot's spatial mobility or its adaptation to predefined criteria of accuracy, speed and movement dynamics.

The sensory subsystem, together with the control and decision-making subsystem, form the so-called cognitive system of the robot, which enables perception of the environment, interpretation of the information obtained and decision-making about further action. The design, modelling and optimisation of robot cognitive systems is part of theoretical robotics, which focuses on the development of algorithms, control architectures and intelligent methods that increase the autonomy and efficiency of robotic systems (Smrček et al., 2007).

1. INDUSTRIAL ROBOTS IN MANUFACTURING PROCESSES AND THEIR CHARACTERISTICS

An industrial robot is an automated technical system designed primarily for handling and technological operations, equipped with a programmable control system. Its basic function is to perform movement and control tasks in the manufacturing process, thereby replacing or supplementing human labour in the movement of materials, the operation of production equipment and the performance of technological operations such as welding, machining, assembly or surface treatment (Smrček & Kárník, 2008).

Industrial robots and manipulators (PRaM) can be characterised as complex electromechanical systems with a high degree of integration of electronic and information elements. These systems are capable of performing activities involving gripping, carrying, machining and, in some cases, assembling objects. Their functionality is based on the close cooperation of individual system components, in particular sensors, integrated computing units and control algorithms, with interaction with human operators also playing an important role in the supervision, programming or optimisation of the production process (Bekey et al., 2008).

From a design perspective, industrial robots are designed with an emphasis on modularity, clear configuration and easy access to individual components, which greatly facilitates their service and maintenance.

Robotic systems are also characterised by a high degree of mobility, as they can usually be moved within the workspace without the need for major changes to the control programme. In addition, their functionality can be expanded by adding new movement sequences or technological operations. These features contribute to the high speed, reliability and low maintenance requirements of robotic systems. Compared to conventional CNC machining centres, industrial robots have lower space requirements, which allows them to be installed in close proximity to the parts being handled or machined, mainly due to their specific kinematic structure and open workspace geometry.

Industrial robots and manipulators differ from conventional production machines in several characteristic features. Among the most important is goal orientation, which consists of the ability to break down a complex task into partial, sequentially executable steps. Another key feature is flexibility, enabled in particular by the automatic exchange of end effectors, which allows the robot to adapt to different technological requirements. Another important aspect is programmability, which ensures the universal use of the robot in a wide range of applications. Robots are also capable of autonomous operation, i.e. performing tasks without continuous direct human assistance. Another important feature is the ability to exchange information with the environment through communication interfaces and sensory systems. Last but not least, they have the mechanical ability to interact with their environment, primarily to grasp, move and position objects in space (Velíšek et al., 2005).

In terms of system organisation, PRaMs can be considered complex technical systems consisting of three basic, interconnected subsystems. The first is the perception or sensory subsystem, which includes a set of sensors monitoring the robot's external environment as well as its internal operating states. The second is the control subsystem, which processes information from the sensory subsystem and input data from the control programme, on the basis of which it plans, coordinates and optimises the robot's activities. The third is the actuation subsystem, which ensures the mechanical interaction of the robot with its surroundings through drives, transmission mechanisms and an end effector, enabling the performance of physical operations in the workspace. From a kinematic point of view, the robotic system consists of two basic mechanical segments, namely a stationary and a moving segment.

The stationary segment is firmly anchored in the space in which the robot moves and usually forms the basis of the entire system. The mobile segment is kinematically linked to the stationary part by means of joint connections and is inseparably connected to the tool or functional component through which the robot performs the required handling or technological operations. The description of the movement of the tool or end effector of the robot represents the application of the principles of kinematics and geometry in the field of robotics, including the analysis of the position, orientation, velocity and acceleration of individual links of the mechanism in space (Karger & Kargerová, 2000).

When evaluating the properties and capabilities of industrial robots, two basic approaches are generally used in technical practice and research. The first is a detailed analysis of the robot's ability to perform a specific elementary operation at a precisely defined point in the workspace. This approach focuses on assessing geometric properties, positioning accuracy, kinematic and static characteristics, as well as analysing the motion control algorithms used. The second approach is a comprehensive or global assessment of the robot's properties based on a set of results achieved in the performance of several elementary operations of a certain type. Such an assessment is determined by integrating partial results for different configurations of the handling system and provides an overall picture of the robot's operational capabilities within its workspace (Jazar, 2010).

The characteristics of industrial robots are significantly influenced by their basic technical parameters, which are closely related to the robot's design. One of the most important technical specifications is the payload, which is defined as the maximum permissible weight of the manipulated object, including the end effector, that the robot is capable of safely moving under specified operating conditions, such as speed of movement, arm reach or dynamic load. Another important parameter is the number of axes of motion, which determines the number of degrees of freedom of the robot with respect to its reference coordinate system and directly affects its flexibility and ability to position the tool in space. Another key characteristic is positioning error, which includes positioning accuracy and repeatability, which are particularly important in applications requiring high precision.

An equally important parameter is the robot's working zone, defined as the spatial range that the robot is capable of reaching with its end effector (Jurišica et al., 2005). An important feature of industrial robots is reachability, which expresses the robot's ability to achieve the desired position and orientation within its working space. This characteristic is assessed based on the range or volume of the robot's working space and its kinematic structure. The reachability analysis involves determining the overall size of the working space, identifying the position vector of the tracked point, and verifying that this point belongs to the robot's reachable area. The analysis also includes determining the angle φ, or orientation parameters, which ensure the required positioning and orientation of the end effector at a given point P.

When defining the robot's working area, several sub-types of spaces are distinguished, which differ in their meaning and purpose. The motion space is the area occupied by all moving parts of the robot except the end effector. The maximum space is an extension of the movement space by the area that can be reached by the end effector together with the manipulated object. The defined space is defined as a specific part of the maximum space that is bounded by safety and protection mechanisms that prevent it from being exceeded, even in the event of a robot malfunction. The operational space is the part of the defined space that is actively used in the performance of programmed work tasks. The working space of a robot includes the set of all positions that the reference point of the robot's wrist can reach in relation to the coordinate system of the base and represents a basic parameter in the design and optimisation of robotic workplaces (Jurišica et al., 2005).

2. BASIC PRAM DESIGN SOLUTIONS – KINEMATIC STRUCTURE OF ROBOTS

PRaMs are defined as mechanical systems whose main function is to transmit movements and forces, transform one type of mechanical movement into another, or guide objects along a specified path. The concept and kinematics of PRaM's moving components are often inspired by the simulation of the movements and motor skills of the human hand or arm (Velíšek et al., 2005).

The kinematic structure of PRaM and its subsequent movement capabilities are defined by the type and arrangement of kinematic pairs within its chain. By combining individual links connected by translational and rotational kinematic pairs, it is possible to assemble various kinematic structures. The flexibility of manipulation of these chains is directly proportional to the number of integrated kinematic pairs and their mutual spatial arrangement. Since these are kinematic pairs with one degree of freedom, the total number of degrees of freedom of the mechanism is equal to the number of kinematic pairs used (Velíšek et al., 2005, Jazar, 2010).

There are a number of open and closed kinematic structures with variable arrangements of individual links and their mutual connections. Each design has unique characteristics that define the scope of its potential application. Robotic mechanisms are assembled from kinematic pairs and their spatial connections, which together form a kinematic chain. The architecture of the kinematic chain is of key importance because it significantly shapes the overall appearance and construction of individual industrial robots (Velíšek et al., 2005, Sandler, 1991). In terms of kinematic structure, robotic systems are typically classified as serial or parallel, and this classification fundamentally influences their motion characteristics, accuracy, rigidity and area of application. The kinematic structure of a robot determines the relationships between the individual links of the mechanism and the way in which the movement of the individual axes is projected into the resulting movement of the end effector.

Serial kinematic chains, often referred to as open kinematic structures, consist of a series of successive links connected by kinematic joints, each of which usually has one degree of freedom. These joints can be translational or rotational, or a combination of both. The movement of each link is gradually accumulated with the movement of the other links in the chain, determining the final position and orientation of the end effector or TCP (*Tool Centre Point*). The resulting geometric shape of the workspace is directly dependent on the specific arrangement and type of individual axes. For example, the TTT configuration generates a rectangular workspace, the RTT configuration generates a cylindrical workspace, the RRT configuration generates a spherical workspace, and the RRR configuration generates a spherical workspace.

For example, the TTT configuration generates a rectangular workspace, the RTT configuration a cylindrical workspace, the RRT configuration a spherical workspace, and the RRR configuration a torus workspace. The main disadvantages of serial kinematic chains include a gradual increase in bending and torsional loads towards the end effector, which leads to a reduction in system stiffness and a deterioration in positioning accuracy (Velíšek et al., 2005). For this reason, these structures often require the use of more robust structural elements, which has a negative impact on the overall weight, dynamic properties and energy consumption of the robot. Figure 1 shows the types of kinematics structures of industrial robots.

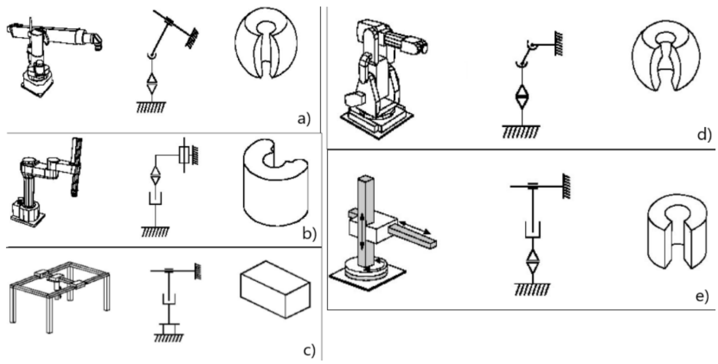

Figure 1. Types of kinematic structures and shapes of their workspaces; a) spherical robot, b) SCARA robot, c) cartesian robot, d) cylindrical robot, and e) angular robot. Adapted from Kusá, (2016).

Parallel kinematic structures, also known as closed kinematic chains, are characterised by the fact that the movement of individual components is directly dependent and coordinated with each other. In these systems, the end effector is carried by several simultaneously acting arms, and its position and orientation are the result of a combination of linear or rotational movements of active and passive members. The individual arms are usually connected by ball, gimbal or universal joints, which allows for high spatial mobility while maintaining high system rigidity. Parallel kinematic structures are characterised by high operating speed, precise positioning and favourable dynamic properties.

A typical representative of this category is the hexapod, whose design principle allows for effective load distribution and significant reduction of bending and torsional stresses. As a result, these systems achieve low total weight of moving parts, high natural frequencies and relatively simple installation.

Despite the above advantages, parallel kinematic structures also have certain limitations. The most significant of these include limited flexibility when changing tools or technological configurations, higher sensitivity to temperature changes and deformation of load-bearing elements, as well as an unfavourable ratio between the achievable working space and the total volume occupied by the robot during operation. These factors may limit their use in applications requiring a large working range or high variability in the production process.

Current developments in serial and parallel kinematic structures are primarily focused on optimising the number of controlled axes, increasing structural rigidity and improving the dynamic properties of robotic systems. The main goal of these efforts is to ensure precise, stable and economical movement of the tool or workpiece in technological processes, especially in machining applications where high demands are placed on the accuracy, repeatability and efficiency of the production process.

3. MANIPULATOR DRIVE UNITS

Drive systems are one of the key components of robotic systems, as they significantly influence their movement, dynamic and precision characteristics. The basic function of a drive system is to transform the supplied primary energy into mechanical movement of the individual axes of the robot, thereby ensuring the performance of handling and technological operations.

Each drive unit usually consists of an electric or fluid motor, a control block ensuring regulated energy supply to the motor, and a connecting mechanism that transfers torque or force from the motor output to the moving part of the motion unit. The transfer of motion can be carried out either directly or via a transmission or transformation block, whose task is to adapt the speed, torque or force to the requirements of a specific application.

In terms of the type of input energy, the drive units of industrial robots are classified as electric, fluid (hydraulic and pneumatic) and combined. Electric drives are currently the most widespread due to their high efficiency, control accuracy and ease of integration into control systems. Hydraulic drives are mainly used where high power and high positional rigidity are required, while pneumatic drives are used in applications with lower accuracy requirements and higher dynamics.

Three basic types of transmission mechanisms are used in the design of drive systems: mechanical, magnetic and electrical. Mechanical transmissions are the most widespread and include a wide range of design solutions such as gear transmissions, rack mechanisms, cam mechanisms, lever systems or chain transmissions. In recent years, the use of modern harmonic and cycloidal gearboxes has become widespread, enabling high transmission ratios while maintaining compact dimensions and high efficiency, thus promoting the effective use of electric motors. Magnetic transmissions are based on the transfer of torque through the magnetic fields of permanent magnets and enable contactless transmission of motion. Electrical transmissions are implemented by pairs of synchros, whose windings are interconnected and enable synchronised transmission of angular position.

Magnetic and electrical transmissions are mainly used in specific robotic applications, such as systems operating in a vacuum or in high-pressure environments, for example in underwater robots. In these applications, it is often necessary to hermetically separate the motors and sensitive electronic components from the surrounding environment, thereby increasing the reliability and service life of the system.

The drive systems of industrial robots are subject to a number of essential requirements in the manufacturing process, including smooth start-up and braking, high positioning accuracy, sufficient positional rigidity, minimum weight and dimensions, and suitable spatial arrangement. Meeting these requirements is essential to ensure smooth, stable and vibration-free handling and technological operations. Smooth start-up and braking of motion units is important for the safe gripping of the manipulated object, as less gripping force is required for vibration-free movement.

At the same time, this minimises the oscillation of the working heads around the target position, which could occur as a result of insufficient system rigidity. Shock loads lead to increased wear of mechanical parts, undesirable stress on the structure and a shortened service life of the robotic system, thereby negatively affecting its reliability.

The high positioning accuracy of the end effector is influenced by several factors, including the kinematic structure of the robot, the rigidity of its structure, the quality of drive control, and the method of sensing the current position. In terms of motion control, a distinction is made between control along individual axes in an open control system and control in a closed control system with feedback, where the position of the end effector is continuously corrected based on information from position sensors.

Sufficient positional rigidity is the ability of the drive system to maintain the achieved position even when external forces are acting on it. This property is particularly important for intermittent and reversible movements, which are typical for robotic manipulators. High positional rigidity is characteristic, for example, of hydraulic drives, where it is achieved by blocking the working fluid in the hydraulic circuit. Electric motors and pneumatic drives have lower inherent stiffness, which is often compensated for by the use of mechanical brakes or appropriate control strategies, although these solutions can negatively affect other drive requirements.

Minimising the weight of the drive system is particularly important in serial kinematic structures, where the drives are integrated directly into the individual links of the handling mechanism. Reducing the weight of moving parts leads to improved dynamic properties, reduced inertial forces and increased energy efficiency of the entire system. Closely related to the requirement for low weight is the requirement for compact dimensions of the drive units, which allow for optimal spatial arrangement of the robot and prevent the working space from being covered by structural elements.

4. OVERVIEW OF ROBOTIC MACHINING ISSUES

Today, industrial sectors rely heavily on robots for tasks such as material handling, assembly, welding and machining. Annual robot sales in 2011 reached approximately 139,300 units.

However, this design represents only a fraction of the plans of Asian manufacturing companies, which intend to significantly expand their robotic capacities. There are expectations and efforts to have robots take over the tasks of machine operators in machining. This trend suggests that the future growth in the number of industrial robots will be even more dynamic as countries intensify automation in their businesses (He & Chen, 2009).

According to The Robotic Industries Association, robotic machining accounted for less than 5% of all existing robotic applications in 2009, with further significant growth expected over the next three to five years (Robotic Industries Association, 2013). Robotic systems should be designed to machine parts made of harder materials and should be capable of performing various processes with tighter tolerances (Robotic Industries Association, 2013). Although robotic machining is not expected to fully replace CNC machining, it is currently considered a suitable alternative for machining non-metallic and some metallic materials, depending on their hardness, the required surface quality and the geometric complexity of the workpieces.

Current companies are responding to market demands not only by adapting existing robots with end effectors, but also by developing specialised robots designed exclusively for machining. An example is the design of the RX 170 HSM machining robot, developed and designed by the authors (Marek, 2010), which is based on the design of a six-axis robot. The key difference is the arm, where a high-speed spindle has been integrated instead of the sixth axis (wrist). The aim of the design was to achieve maximum rigidity in order to minimise vibrations during the cutting process. With a robot of this design, a repeatable accuracy of ± 0.04 mm was achieved. The cables and hoses for lubrication and cooling were routed inside the robot arm to increase safety and smoothness of movement (Marek, 2010).

In addition to design aspects, the studies also pointed out that a persistent lack of information and knowledge among end users about the advantages and operation of machining robots is an obstacle to their wider adoption (Robotic Industries Association, 2013). As a result, leading global manufacturers of industrial robots have begun to supply machining robots with comprehensive software packages such as RobotStudio and Roboguide (KUKA Robot Group, 2013).

Before their direct deployment in machining, studies were conducted that confirmed the ability of robots to perform operations such as polishing, grinding and deburring (FANUC Robotics, 2013). However, the results vary in the field of milling. In milling, the low repeatability of serial robots for this technology has proven to be a problem. This is because the robot arm must withstand considerable loads when machining different materials. Insufficient rigidity of the robot can lead to significant inaccuracies in machining. To overcome the disadvantages of articulated robots, the European Commission initiated and funded the COMET project (Plug and Produce COMponents and METhods for adaptive control of industrial robots enabling cost effective, high precision manufacturing in factories of the future) in 2009. The aim of the project was to develop methods for the adaptive control of industrial robots that would ensure cost-effective and highly accurate production in the future. The project also focused on addressing challenges in manufacturing sectors and developing innovative machining systems that would be flexible, reliable and cost-predictable compared to traditional machine tools. The use of industrial robots for chip machining technologies was chosen as the basis for the project. The project implementers were aware of the weaknesses of industrial robots, such as lower positioning accuracy, vibrations caused by cutting forces, and the absence of reliable programming tools. Despite these challenges, the project was expected to significantly advance robotic machining (ABB Robotics, 2013).

Robotic machining technology is advantageous in cases where it serves as an adequate alternative to metal machining in conventional machining centres. Using the proposed robotic equipment and associated software, it is possible to achieve the desired automated solutions and exploit possibilities that were previously the domain of conventional machining centres for chip machining.

A key obstacle to the use of robots in the machining of structural materials, especially metals, is ensuring sufficient accuracy and rigidity of their construction. Conventional articulated robots typically achieve a rigidity of approximately 1 N/µm. This is significantly less than conventional CNC machines, which typically achieve 50 N/µm and more, especially when considering that the tool tip is attached to a long robot arm (He & Chen, 2009).

The repeatability of articulated robots is inherently linked to their reach. As the reach distance increases, repeatability decreases. The positioning accuracy of the arm therefore depends on its length. These positioning accuracy and repeatability data are also provided by robot manufacturers (see Table 1). The table provides basic parameters for selected Fanuc robot models (FANUC Robotics, 2013).

Table 1. Reach and repeatability of robots from FANUC (FANUC Robotics, 2013).

Robot model	Arm reach [mm]	Repeatability (positioning accuracy) [mm]
M-10iA/10M	1420	± 0.08
M-710iC/50	2050	± 0.07
M-900iA/350	2650	± 0.3

The above information shows that as the arm's reach increases, so does the positioning accuracy error. The table also confirms that the repeatability of modern industrial robots (± 0.01 mm) is sufficient for low to medium precision machining. In fact, most machining operations do not require a long arm reach.

Another key factor is the rigidity of the robot. Higher rigidity can be achieved by using robots with parallel guidance, but this leads to a reduction in the working space. Robots are currently used in machining, specifically for deburring castings, finishing, polishing and grinding soft materials such as foams, plastics, wood, aluminium and sand moulds, where there are no significant reaction forces that would cause robot deviations. Robots are also used in other material processing methods, such as laser or water jet cutting. An example is the automotive industry, where aluminium and plastic parts are manufactured by casting and subsequently require deburring or surface treatment. Currently, most of these operations are performed manually in noisy and dusty environments, so there is an effort to automate them (Yhman s.r.o., 2011).

A significant advantage of robots in machining is their large working space and relatively small footprint compared to standard machining centres, as well as the ±185° rotation range of robots with serial arms, which allows for the machining of a wide range of workpieces, including large and complex parts. High flexibility is also achieved through the use of eight or more axes.

After changing the tool head, the robot can handle workpieces, perform assembly operations and work continuously, 24 hours a day. The current trend in robotic machining indicates an effort to replace large CNC machines in chip machining applications that do not primarily focus on extensive material removal, but rather on finishing operations such as polishing, grinding, and the like. This is also related to the need to increase the accuracy of robots in machining. A key part of this effort is the development of software tools that improve robot motion corrections and compensate for existing inaccuracies in its design. As already mentioned, the chosen method of robot control and programming is equally important (Chen & Dong, 2012).

5. CONTROL OF INDUSTRIAL ROBOTS AND TYPES OF END-EFFECTOR MOVEMENT

The robot is controlled by a control system that processes data obtained from sensors. This system allows the robot to be guided to the desired positions using a programming unit (pendant). Through input/output interfaces, it is possible to connect additional robotic workstation devices, such as conveyors or positioning tables, to the robot control unit, enabling the control of additional system axes. The robot control system generates control signals for individual axes; servo drives and other robot actuators (Vitralab, 2011).

When programming a robot, an important task is to control its basic movements. Robot control in terms of defining the movement trajectory determines the basic principles of entering movement commands. The program commands themselves include information about the type of movement, its speed, and any path approximation (Schmid et al., 1998).

Depending on the nature of motion control, we distinguish between different types of industrial robot control. Point-to-point (PTP) control is used in cases where it is necessary to reach precisely defined points in the robot's workspace, while the course of motion between these points is not essential. Continuous path (CP) control is used when it is necessary to control the robot's movement along its entire trajectory. Figure 2 shows the general movement of an industrial robot.

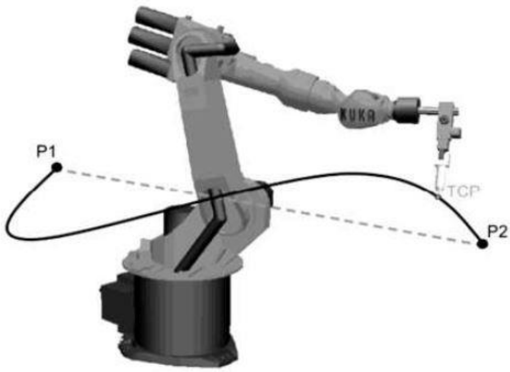

Figure 2. General movement of an industrial robot (Pochylý, 2012).

The robot's end effector, referred to as TCP (*Tool Centre Point*), performs movements based on a predefined path, speed and technological purpose of the given operation. Depending on the application requirements and the method of motion control, there are several types of TCP movements. General motion is the basic method of moving the end effector, in which the path can be a straight line, a curve or part of a circle. The actual course of the trajectory depends on the set speed of movement and the current configuration of the individual axes of the robot. This type of movement is mainly used in cases where it is not necessary to precisely define the path between individual points, but it is crucial to reach specific positions in the robot's working space, for example when handling parts or spot welding. Linear motion (see Figure 3) is characterised by the direct movement of the TCP from its initial position to a precisely defined end point, with the end effector moving in a straight line during the motion. The trajectory of this movement is described by parametric equations and is particularly suitable for applications requiring constant speed and precise adherence to the movement path, even in environments with obstacles. Linear motion is often used in precision welding processes, machining or other technological operations where high tool trajectory accuracy is essential.

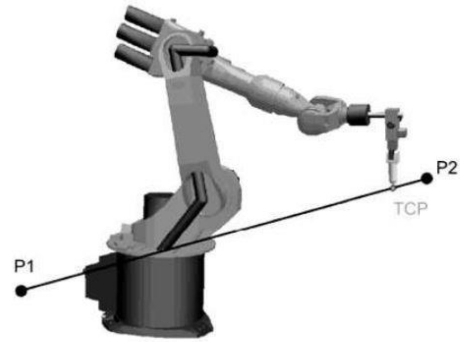

Figure 3. Linear motion (Pochylý, 2012).

Circular motion (see Figure 4) TCP is defined by the movement of the end effector along a circular path between the start and end points, with the path determined by one or more auxiliary points. This type of motion allows for smooth transitions along arcs with a precisely defined radius and path orientation. After reaching the end point, the tool can change the direction or orientation of its movement depending on the technological requirements. Circular motion is mainly used for machining complex surfaces and for programming the tool reference point, where the emphasis is on smoothness and precision of movement.

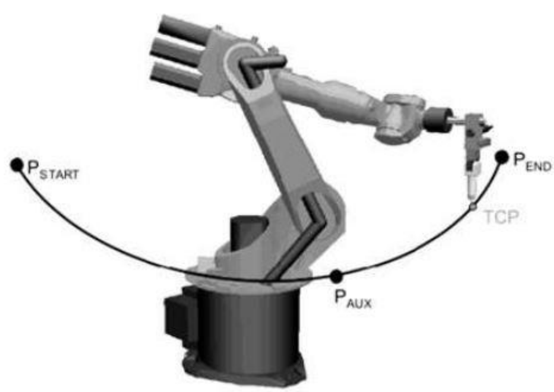

Figure 4. Circular motion (Pochylý, 2012).

6. PROGRAMMING INDUSTRIAL ROBOTS

The programming of industrial robots is considered a complex and systematic process in which it is not sufficient to determine only the position of the robot in space, but it is also necessary to precisely define the orientation of the end effector or the method of gripping the manipulated part. This requirement is particularly important in assembly, machining and handling operations, where incorrect tool orientation can lead to technological errors or a reduction in the quality of the final process.

The robot's tasks are performed on the basis of a pre- ly prepared control program, which contains sequentially defined commands ensuring the implementation of individual technological and handling activities. The creation of the program is based on the design of an algorithm in which the sequence of operations, the conditions for their execution and the interrelationships between the individual movements of the robot are precisely specified.

Depending on the approach used to create the control programme, the following basic methods of industrial robot programming are distinguished:

- On-line programming, in which the programme is created directly on the actual robotic device, most often via a programming panel, with the individual positions and movements being recorded in the control system's memory in a learning mode,
- Off-line programming, in which the programme is prepared in an external software environment based on a virtual model of the robot and the workplace and is then transferred to and verified in the robot's control system (Vitralab, 2011).

To accurately determine the positions of reference points in space, coordinate systems are used in robot programming, which allow the mutual position of the robot, individual elements of the robotic workplace and objects manipulated or machined by the robot to be clearly defined. In practice, a common reference coordinate system is usually applied, which ensures uniform orientation and consistent description of all position data. Four basic types of coordinate systems (see Figure 5) are commonly used in the programming of most industrial robots (Schmid et al., 1998):

- WORLD coordinate system (WSC) – This Cartesian coordinate system is firmly connected to the robot base and is defined as a stable and unchanging reference frame. It is used to determine the global position of the robot in space and represents the basic coordinate system from which other coordinate systems are derived, in particular the BASE system and the robot base coordinate system. Due to its stability, it is used as the main reference system in the design and calibration of robotic workstations (Vitralab, 2011).
- Coordinate system "BASE" (Wobj.) – The BASE coordinate system defines the position and orientation of the workpiece relative to the WORLD coordinate system. Its axes are oriented depending on the geometry of the workpiece or the base of the technological equipment, such as a positioning or rotary table. It allows the robot's movements to be defined so that they are directly linked to the workpiece, which is particularly advantageous when changing its position in the workspace. This coordinate system is primarily used for off-line programming and for defining the trajectories of robot movements in technological processes (Vitralab, 2011, Schmid et al., 1998).
- Robot base coordinate system (BF&TF) – This coordinate system is related to the mechanical base of an industrial robot and determines its position and orientation relative to the WORLD coordinate system. In standard applications, this system is identical to the WORLD system, but in specific cases it can be defined separately, for example when relocating the robot or installing it on a mobile or positionable platform (Vitralab, 2011, Schmid et al., 1998).
- Tool Coordinate System (TCP) – The origin of the TCP coordinate system is defined at the reference point of the tool, referred to as the Tool Centre Point. This system determines the position and orientation of the end effector in relation to the workpiece or the BASE coordinate system. In this system, the x-axis is usually oriented in the direction of the tool's working movement. When the robot moves, the position of this coordinate system also changes, and it is necessary for the user to set it precisely to the central point of the tool to ensure the correct execution of technological operations (Vitralab, 2011, Schmid et al., 1998).

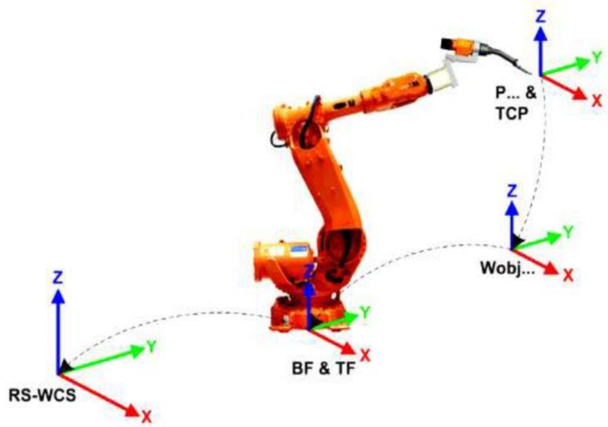

Figure 5. Coordinate systems of industrial robots (ABB Robotics, 2010).

6.1 On-Line Programming of Industrial Robots

The online programming method is based on the operator directly guiding the robot along the desired trajectory of movement. In this case, the robot's movements are controlled via a programming panel, with individual positions, orientations and transitions being recorded in the robot's control system memory.

After defining the desired path, the logical part of the robotic arm control is configured and the functions of the associated peripheral devices of the robotic workstation, such as positioning tables, conveyors or safety elements, are set. This phase also includes assigning speeds, or acceleration and deceleration, to individual movement sequences for a predefined robot trajectory (Schmid et al., 1998, ABB Robotics, 2010).

Modern programming units are now often connected to computer systems, which allows for expanded control and visualisation options for programming processes. The robot is controlled by function buttons or joystick-type controllers or six-axis mice, which control the robot's movement with high precision. A typical example of a portable control device is the so-called teach pendant, which allows local or remote control of the robot without the need for a direct connection to a fixed control panel. This expands the possibilities for deploying the robot in various operating conditions.

From a safety perspective, the programming panel is equipped with an emergency stop button, which immediately interrupts the current operation in the event of a collision, non-standard behaviour or other malfunction, preventing damage to the end effector, robot or surrounding equipment. The programming panel display is used to display, edit and check program commands, as well as to view the history of operations performed. Together with the integrated keyboard, whose design and layout depends on the specific robot manufacturer, it forms the basic interface for entering and editing data.

One form of online programming is the playback method. Its principle is that the robotic arm is physically guided along the desired trajectory, while the control system continuously records the course of the movement. The positions and orientations of the individual robot joints are scanned and stored at extremely short time intervals, creating a detailed record of the entire trajectory. During subsequent operation, this trajectory is reproduced automatically without the need for further operator intervention. This method is characterised by its simplicity and speed of programming, but its use is limited mainly to applications where there are no high demands for flexibility and precise path modification.

Another important method of online programming is Teach-in. This technique is based on the gradual definition of key robot positions, known as teaching points. The robot is manually guided to precisely defined positions using the controls on the programming panel, such as buttons or a six-axis mouse. The geometric coordinates of these points, together with the orientation of the end effector, are stored in the memory of the robot's control unit. The actual technological operations to be performed at these points, as well as the logical links between the individual points, are defined additionally in the next phase of programming (Vitralab, 2011, ABB Robotics, 2010).

In current industrial applications, teach pendants are typically physically connected to the robot's main control panel via a cable connection. This limits the maximum distance from which the robot can be safely controlled. At the same time, it is typical for a single programming panel to be designed to control a specific robot or robotic system, which can reduce flexibility when operating larger robotic cells (Schmid et al., 1998).

6.2 Off-Line Programming of Industrial Robots

The primary goal of most robotic system manufacturers is to implement the programming of industrial robots in off-line mode. This approach allows for flexible and rapid changes in the production process, easier integration of new products or variants, and the achievement of full production capacity while maintaining high production quality in a relatively short time frame. Thanks to offline programming, it is possible to prepare and verify control programs even before the physical installation of robots and technological equipment, which represents a significant time and organisational advantage. Once the robotic workstation is put into operation, the programs are immediately ready to start the production process without the need for long-term interventions in the operation (Occupational Safety & Health Administration, 2013).

The success of offline programming depends on the precise alignment of the virtual model of the robotic workplace with the actual physical environment. The key factor is the geometric accuracy of the real layout of the workplace in relation to the designed and modelled values, as well as the correct definition of the kinematic and dynamic parameters of the robot and its peripheral devices. In a simulated robotic environment, robots can be programmed using a computer, with control programmes being created, analysed and optimised without the need for direct intervention in actual production. This approach leads to an increase in overall productivity, as there is no need to interrupt the production process during programming or testing of new tasks.

Offline programming allows the creation of realistic simulations based on actual robotic programs and configurations that are identical to those subsequently used in real production. A significant advantage of this approach is also increased safety, as there is no risk of operator injury, end effector damage or collisions caused by technical malfunctions or operator errors in a virtual environment (Vitralab, 2011). Control programmes can be created, verified and optimised exclusively in a digital environment, eliminating the need for the simultaneous availability of all hardware and technological means of production, while minimising the need to interrupt production until the programme is uploaded to the robot's control system.

Offline programming is performed in a computer model of a real robotic cell, which is usually loaded from a database and supplemented with a detailed three-dimensional model of the surrounding working environment. Three-dimensional models of individual components can be created directly within the offline programming software or imported from external CAD systems. Specific programming languages or graphical environments are often used to create control programs, which require the use of a compiler for correct interpretation. The task of the compiler is to convert a general program into the specific syntax and structure of the control system of a given type of robot (Pochylý, 2012).

Another significant advantage of offline programming is the possibility of programming in advance. Control programmes can be created and optimised outside the actual robot workplace, without time pressure and without the constraints of maintaining smooth production. This significantly reduces downtime associated with changes in the production programme and the reconfiguration of robotic workplaces.

The main advantages of offline programming can be summarised as follows (ABB Robotics, 2010):

- increased production efficiency due to minimised downtime and parallel programming and production processes
- automatic optimisation of the robot's movement path, including detection of possible collisions and automatic obstacle avoidance,
- simplification and streamlining of the programming process, leading to a reduction in the risk of errors in the control programme,
- direct integration of off-line programmes with CAD systems, enabling rapid transfer of geometric data to the programming environment,
- the ability to program movements along complex and spatially demanding curves, which is particularly important in CAM applications such as robotic machining or laser processing.

One of the main disadvantages of offline programming is its higher cost. These costs go beyond the purchase price of the robot itself and mainly include the cost of specialised software tools, licences, compilers and, in some cases, operator training.

Nevertheless, offline programming is considered an effective and promising approach in modern industrial applications, contributing significantly to increasing the flexibility, safety and competitiveness of production systems (Schmid et al., 1998). In the initial phase of offline programming, it is necessary to determine the geometric model of the object, which forms the basis for further simulation and motion planning steps. Most modern CAPE tools have integrated functions that allow the creation of basic geometric shapes that are used to model simple components of a robotic system. However, in order to achieve a high degree of realism in the simulation, a real three-dimensional model of the robot supplied by its manufacturer is usually used, which already has a precisely defined geometry, kinematic structure and ranges of motion of the individual axes. Alternatively, custom geometry with unique kinematics can be designed, or the kinematics of an existing model can be modified depending on the specific requirements of the application.

The basic geometric shapes represent the individual links of the robotic arm and their interconnections, i.e. the robotic joints. In the case of a typical industrial robot with six degrees of freedom, it is necessary to clearly define six axes of motion (Pochylý, 2012). Each joint is characterised by a fixed and a movable part, as well as an axis of motion that determines the centre of rotation or translation of the given link. In order to achieve realistic model behaviour, it is also necessary to set the limit values for the movements of individual joints in advance. For this purpose, the technical data of a real robot is ideally used, as the ranges of motion may differ even for the same types of manipulators deployed in different parts of the production system.

The next step is to define the transition points and describe the robot's motion trajectory. Although not all points on the trajectory represent working positions, the resulting robot path is always formed by a sequence of working and auxiliary transition points. In general, the more complex the access to the working points, the greater the number of transition positions that need to be included in the trajectory planning. Path planning is performed iteratively, point by point, with the aim of reaching the working position with a minimum number of auxiliary points. An excessive number of transition positions can negatively affect the overall cycle time of the robotic cell.

In this context, kinematic simulation plays an important role in identifying critical points and inefficient sections of the planned trajectory (ABB Robotics, 2010). To optimise cycle time, transition points must be positioned and oriented so that the robot makes maximum use of the movements of axes equipped with faster drives. In working positions, the robot's movement is usually performed at lower speeds, as the movement parameters are limited by the requirements for accuracy, quality and stability of the technological process, such as assembly, machining or welding. The correct distribution of fast movements and precise working movements therefore has a fundamental impact on the overall efficiency of the process.

From the point of view of off-line programming implementation, it is advantageous to perform programming in the coordinate system of the product (workpiece). This coordinate system is commonly used in CAD and CAPE systems in which the product is modelled, such as Catia, Robcad and similar tools (Occupational Safety & Health Administration, 2013). Programming in workpiece coordinates allows simple and quick balancing of robot positions and trajectories, especially when changing the geometry of the product or moving it within the workspace. The final and key phase of off-line programming is the compensation of differences between the simulated and real environments, known as calibration. Calibration has a fundamental impact on the practical applicability of offline programming, as an automatically generated programme can only be deployed in real operation if the virtual environment accurately reflects the actual layout of the robotic workstation. The aim of calibration is to precisely align the positions of the robot, tools, workpieces and peripheral devices between the digital model and the real system, thereby minimising the need for additional corrections to the programme after it has been uploaded to the robot control system (Pochylý, 2012).

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