附件 1　　浙江水利水电学院“南浔学者”申请表

<table>
<tr><td>姓　名</td><td>方贵盛</td><td>出生年月</td><td>1973 年 7 月</td><td>参加工作时间</td><td>2000 年 7 月</td></tr>
<tr><td>现所在单位（部门）</td><td>机械与汽车工程学院</td><td>最高学历/学位</td><td>研究生/博士</td><td>专业技术职务</td><td>教授</td></tr>
<tr><td>拟申报类别</td><td colspan="5">二类学者</td></tr>
<tr><td>符合条款</td><td colspan="5">符合二类学者业绩成果（1）主持省部级教学科研重点项目1项和省部级教学科研纵向项目3项：Ⅴ类项目1项，绩点60；Ⅵ类项目3项，绩点90，五类论文2篇，绩点40。总绩点190。</td></tr>
<tr><td rowspan="9">所涉业绩</td><td rowspan="2">教学类
绩点：120</td><td colspan="4">教学-教学重点项目 1 项-60 绩点：
（1）浙江省第二批“十二五”省级实验教学示范中心重点建设项目-机械工程实验教学示范中心，负责人，2015。</td></tr>
<tr><td colspan="4">教学-教材建设 2 项-60 绩点：
（1）方贵盛，三维实体建模与设计，浙江省“十三五”第二批新形态教材建设项目，浙江大学出版社，2020。
（2）方贵盛，电气控制与 PLC 应用，浙江省普通本科高校“十四五”首批“四新”重点教材建设立项项目，2023。</td></tr>
<tr><td rowspan="2">科研类
绩点：70</td><td colspan="4">科研-科研项目-VI 类项目 1 项-30 绩点：
（1）基于仿尺蠖攀爬机器人的水闸钢丝绳在线激光清洗方法研究，浙江省基础公益研究计划项目（项目号：LGG21F030005），主持人，2021。</td></tr>
<tr><td colspan="4">科研-科研成果-V 类论文 2 篇-40 绩点：
（1）Guisheng Fang and Jinfeng Cheng. Design and Implementation of a Wire Rope Climbing Robot for Sluices[J], Machines, 2022,11,1000。(SCI，五类)
（2）Guisheng Fang,Jinfeng Cheng.Advances in Climbing Robots for Vertical Structures in the Past Decade: A Review, Biomimetics, 2023,8(1),47 (SCI，五类)</td></tr>
<tr><td rowspan="2">与上述水平相当的其他业绩</td><td colspan="4">机械工程省级一流学科（B 类）建设项目，负责人，2015。</td></tr>
<tr><td colspan="4">机械设计制造及其自动化省一流建设专业，负责人，2019。</td></tr>
<tr><td>总绩点</td><td colspan="4">190</td></tr>
<tr><td colspan="5"></td></tr>
<tr><td>个人承诺</td><td colspan="5">本人承诺上述所填内容真实、准确；如有不实，本人承担相应责任。
签名：方贵盛　　时间：2023.11.15</td></tr>
<tr><td colspan="6">以上部分由申请人填写，所在单位审核。以下由单位（部门）和学校填写。</td></tr>
<tr><td>所在单位（部门）意见</td><td colspan="5">1.经审核，申请人所填内容：☐属实　☐不属实；
2.是否符合所申请的类别：☐符合　☐不符合；
3.是否同意推荐：☐同意　☐不同意。
负责人签名：　　（部门盖章）
____年____月____日</td></tr>
<tr><td>科技处审核意见</td><td colspan="2">负责人签名：　　（部门盖章）
年___月___日</td><td>教务处审核意见</td><td colspan="2">负责人签名：　　（部门盖章）
年___月___日</td></tr>
<tr><td>其他相关职能部门审核意见</td><td colspan="5">负责人签名：　　（部门盖章）
_____年____月____日</td></tr>
<tr><td>学校意见</td><td colspan="5">（学校盖章）
____年____月____日</td></tr>
</table>

备注：表格请用 A4 纸打印，有关佐证材料附后。

浙江省教育厅办公室文件

浙教办高教〔2015〕101号

浙江省教育厅办公室关于公布第二批“十二五”省级实验教学示范中心重点建设项目的通知

各本科高校:

根据省教育厅《关于“十二五”期间全面提高本科高校教育教学质量的实施意见》（浙教高教〔2011〕170号）和《浙江省教育厅办公室关于开展高校实验教学示范中心建设工作的通知》（浙教办函〔2015〕173号）要求，经学校申报、专家评审，现确定浙江大学光电信息工程实验教学中心等41个实验教学中心（见附件）为“十二五”省级实验教学示范中心重点建设项目（以下简称示范中心）。各示范中心要以培养学生实践能力和创新精神为目标，进一步明确建设思路，完善运行管理机制，加强实验教学队伍建设，创新实验教学模式，更新实验教学方法和手段，

共享优质实验教学资源，提升实验教学质量，充分发挥示范效应。

附件：“十二五”省级实验教学示范中心重点建设项目名单（第二批）

浙江省教育厅办公室

2015年12月8日

浙江省教育厅办公室 2015 年 12 月 9 日印发

附件

“十二五”省级实验教学示范中心重点建设项目名单

（第二批）

序号	学校名称	中心名称	所属专业类	负责人
1	浙江大学	光电信息工程实验教学中心	电子信息类	郑晓东
2	中国美术学院	创意设计实验中心	设计学类	段卫斌
3	浙江工业大学	计算机实验教学中心	计算机类	王卫红
4	浙江师范大学	电工电子实验教学中心	电子信息类	张长江
5	浙江师范大学	化学实验教学中心	化学类	朱钢国
6	宁波大学	物理实验教学中心	物理学类	诸跃进
7	浙江理工大学	生物科学实验教学中心	生物科学类	梁宗锁
8	杭州电子科技大学	机电工程综合实验教学中心	机械类	陈国金
9	浙江工商大学	环境科学与工程实验教学中心	环境科学与工程类	沈东升
10	中国计量学院	食品质量安全及检测实验教学中心	食品科学与工程类	朱　诚
11	浙江中医药大学	听力与言语康复实验教学中心	医学技术类	应　航
12	浙江海洋学院	海洋科学实验教学中心	海洋科学类	郑　红
13	浙江农林大学	农林环境与资源实验教学中心	自然保护与环境生态类	周国模
14	温州医科大学	医学检验诊断学实验教学中心	医学技术类	吕建新
15	温州医科大学	药学实验教学中心	药学类	叶发青
16	浙江科技学院	土木工程实验教学中心	土木类	罗战友
17	浙江科技学院	艺术设计实验教学中心	设计学类	徐　迅
18	浙江传媒学院	广电通信实验教学示范中心	电子信息类	张根源
19	嘉兴学院	材料与轻纺工程实验中心	材料类	易洪雷
20	杭州师范大学	化学实验教学示范中心	化学类	尹守春

21	温州大学	生物实验教学中心	生物科学类	吴明江
22	绍兴文理学院	电工电子实验教学中心	电子信息类	梁　伟
23	湖州师范学院	水产养殖学实验教学示范中心	水产类	叶金云
24	台州学院	制药化工实验教学示范中心	化工与制药类	杨健国
25	衢州学院	机械基础实验教学中心	机械类	周兆忠
26	宁波工程学院	化学化工基础实验教学示范中心	化工与制药类	房江华
27	宁波工程学院	电子技术实验中心	电子信息类	张永平
28	浙江水利水电学院	机械工程实验教学中心	机械类	方贵盛
29	浙江大学城市学院	计算机与计算科学实验教学中心	计算机类	杨起帆
30	浙江大学宁波理工学院	生物与化学工程实验教学中心	综合类	梅乐和
31	浙江理工大学科技与艺术学院	艺术与设计实验教学中心	设计学类	吴永杭
32	浙江工业大学	土木工程防灾减灾虚拟仿真实验教学中心	土木类	许四法
33	浙江海洋学院	海洋运输工程虚拟仿真实验教学中心	交通运输类	谢永和
34	浙江传媒学院	视听媒体虚拟仿真实验教学中心	传媒类	胡一梁
35	嘉兴学院	医学虚拟仿真实验教学中心	医学类	黄　嬛
36	温州大学	现代制造虚拟仿真实验教学中心	机械类	周宏明
37	浙江万里学院	电子信息虚拟仿真实验教学中心	电子信息类	梁　丰
38	丽水学院	计算机应用虚拟仿真实验教学中心	计算机类	潘巧明
39	衢州学院	化工过程与污染控制虚拟仿真实验教学中心	化工与制药类	郑启富
40	浙江广播电视大学	远程开放虚拟仿真实验教学中心	综合类	齐幼菊
41	浙江财经大学东方学院	企业经营管理虚拟仿真实验教学中心	经济管理类	黄董良

我校 6 部教材入选省普通高校“十三五”第二批新形态教材建设项目

来源：教务处文：刘中晓发布时间：2019-04-29

近日，浙江省高等教育学会公布了浙江省普通高校“十三五”第二批新形态教材建设项目评选结果，我校共有《三维实体建模与设计》等 6 部教材获得立项。

新形态教材是在“互联网+教育”背景下高校教材发展新思路和新形式的积极探索，根据浙江省教育厅《关于加快推进普通高校 “互联网+教学”的指导意见》（浙教高教〔2018〕102 号）的精神，我省在“十三五”期间计划共设立 1000 种新形态高等教育教材项目。

学校将继续推动教学与现代信息技术相融合，鼓励教师利用信息技术创新教材形态，将新形态教材与在线开放课程深度融合，推进线上线下混合式教学改革 ，提高课堂教学效果，提升人才培养质量。

序号	教材名称	主编	建设部门	类型
1	三维实体建模与设计	方贵盛	机械与汽车工程学院	修订
2	水工建筑物	周建芬	水利与环境工程学院	新编
3	工程测量	孔维华	测绘与市政工程学院	新编
4	BIM 技术应用——Revit 建模基础	孙仲健	建筑工程学院	修订
5	职业生涯规划	王丽	马克思主义学院	新编
6	工程数学	吴福珍	基础教学部	新编

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我校6部教材入选省普通高校“十三五”第二批新形态教材建设项目

来源：教务处 文：刘中晓 发布时间：2019-04-29

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新形态教材是在“互联网+教育”背景下高校教材发展新思路和新形式的积极探索，根据浙江省教育厅《关于加快推进普通高校 “互联网+教学”的指导意见》（浙教高教〔2018〕102 号）的精神，我省在“十三五”期间计划共设立1000种新形态高等教育教材项目。

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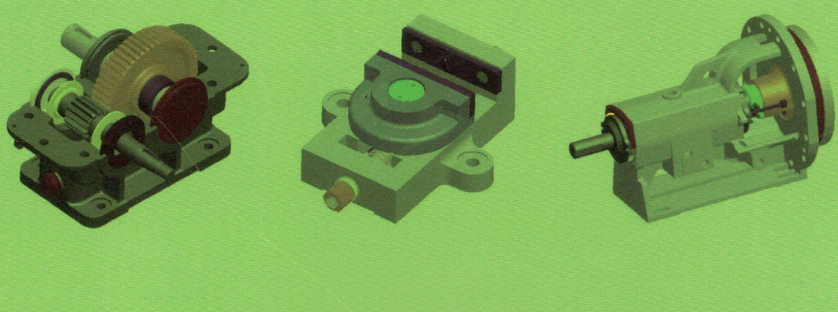
序号	教材名称	主编	建设部门	类型
1	三维实体建模与设计	方贵盛	机械与汽车工程学院	修订
2	水工建筑物	周建芬	水利与环境工程学院	新编

浙江省普通高校"十三五"新形态教材

三维实体建模与设计

Creo（Pro / Engineer）篇

方贵盛◎主　编　江有永◎副主编



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——Creo(Pro/Engineer)篇

主　编　方贵盛
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目录

项目一 01 数字化三维CAD软件认知

认知1　数字化技术与数字化三维CAD软件　/ 1

认知2　数字化三维CAD软件在机电类职业岗位中的应用/ 2

项目二 02 初识Creo(Pro/Engineer)软件

认知1　Creo(Pro/Engineer)软件功能概述　/ 4

认知2　Creo(Pro/Engineer)软件初始界面认知　/ 6

任务1　Creo(Pro/Engineer)三维建模设计初体验　/ 7

项目三 03 二维参数化草绘设计

认知1　草绘设计环境认知　/ 13

任务1　随心所欲绘制二维草图　/ 16

【工程案例一】卡通图形草绘设计　/ 16

任务2　根据尺寸要求绘制二维草图　/ 22

【工程案例二】薄片零件草图绘制　/ 22

任务3　应用几何约束简化草图绘制过程　/ 30

【工程案例三】五角星草图绘制　/ 30

【工程案例四】花状图形草绘设计　/ 33

任务4　综合工程案例实战演练　/ 38

【工程案例五】手柄状图形草绘设计　/ 38

项目四 04 三维零件设计基础

认知1 特征与参数化特征造型 / 43
认知2 三维零件设计环境认知 / 44
任务1 以拉伸方式创建三维零件模型 / 45
【工程案例一】轴承座的三维建模 / 45
任务2 以旋转方式创建三维零件模型 / 55
【工程案例二】定位轴的三维建模 / 55
任务3 以扫描方式创建三维零件 / 62
【工程案例三】弯曲工字钢型材三维建模 / 62
【工程案例四】茶杯的三维建模 / 66
任务4 以截面混合方式创建三维零件 / 73
【工程案例五】组合体模型的三维建模 / 73
任务5 构造特征在三维建模中的综合应用 / 85
【工程案例六】落料凹模的三维建模 / 85
【工程案例七】端盖的三维建模 / 92
【工程案例八】支座的三维建模 / 97
【工程案例九】戒指的三维建模 / 104
任务6 基准特征在三维建模中的综合应用 / 110
【工程案例十】固定座的三维建模 / 115
任务7 特征的编辑与修改 / 123
认知1 特征的编辑与修改 / 123
综合工程案例实战演练 / 128

项目五 05 复杂零件三维设计

任务1 以螺旋扫描方式创建三维零件 / 132
【工程案例一】弹簧的三维建模 / 132
【工程案例二】螺母的三维建模 / 134
【工程案例三】变螺距弹簧的三维建模 / 140
任务2 以混合特征方式创建三维零件 / 143
【工程案例四】绞刀头的三维建模 / 143

任务3 以扫描混合方式创建三维零件 / 147

【工程案例五】吊钩的三维建模 / 147

【工程案例六】方向盘的三维建模 / 153

任务4 以可变剖面扫描方式创建三维零件 / 159

【工程案例七】塑料瓶的三维建模 / 159

任务5 以环形折弯方式创建三维零件 / 164

【工程案例八】汽车轮胎的三维建模 / 164

任务6 以骨架折弯方式创建三维零件 / 169

【工程案例九】风车的三维建模 / 169

任务7 以曲面建模方式创建三维零件 / 173

【工程案例十】水槽的三维建模 / 173

【工程案例十一】吹风机的三维设计 / 187

任务8 齿轮零件三维参数化建模设计 / 200

【工程案例十二】齿轮的三维建模设计 / 200

综合工程案例实战演练 / 213

【综合案例练习一】 / 213

【综合案例练习二】 / 213

【综合案例练习三】 / 214

06 项目六 零件装配与运动仿真

认知1 装配环境认知 / 216

认知2 零件装配模式 / 217

任务1 零件装配与分解 / 217

【工程案例一】轴承座零件装配 / 217

【工程案例二】深沟球轴承零件装配 / 230

【工程案例三】千斤顶零件装配 / 236

任务2 机构运动仿真 / 247

【工程案例四】千斤顶机构运动仿真 / 247

【工程案例五】齿轮泵机构运动仿真 / 257

【工程案例六】铰链四杆机构运动仿真 / 279
综合工程案例实战演练 / 290
【综合案例练习一】阀零件装配 / 290
【综合案例练习二】定位器零件装配 / 293
【综合案例练习三】虎钳零件装配与运动仿真 / 294

项目七 07

工程图绘制

任务1 工程图图框及标题栏设计 / 298
【工程案例一】A4标准图框与标题栏制作 / 298
任务2 基本视图创建与尺寸标注 / 306
【工程案例二】套接件的工程图制作 / 306
任务3 剖视图创建与尺寸标注 / 316
【工程案例三】支座的工程图制作 / 316
【工程案例四】轴承内圈的工程图制作 / 321
【工程案例五】连接套零件的工程图制作 / 326
【工程案例六】落料凹模零件的工程图制作 / 331
任务4 其他视图的创建 / 335
【工程案例七】支架零件的工程图制作 / 335
【工程案例八】轴零件的工程图制作 / 342
综合工程案例实战演练 / 356

项目八 08

三维实体建模与设计综合训练项目

任务1 齿轮泵三维零件建模设计与零部件装配 / 358
任务2 减速器三维零件建模设计与零部件装配 / 361
任务3 风扇三维零件建模设计与零部件装配 / 369

附录1 CAD技能等级考评大纲 / 371
附录2 CAD技能等级考试样题(中级) / 374
参考文献 / 378

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2022年12月19日

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浙江省基础公益研究计划

项目计划书

立项编号	LGG21F030005
项目名称：	基于仿尺蠖攀爬机器人的水闸钢丝绳在线激光清洗方法研究
计划类别：	公益技术研究计划
项目类别：	工业
项目负责人：	方贵盛　　电话：　13606620840
电子邮箱：	823180313@qq.com
通信地址：	浙江省/杭州市/江干区 .下沙高教园区东区学林街 583 号浙江水利水电学院机械与汽车工程学院
邮政编码：	310018
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申报日期：	2020-11-27

浙江省科学技术厅

浙江省自然科学基金委员会

二O二O年制

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一、收到《浙江省基础公益研究计划项目立项通知》后，请认真阅读省基础公益研究计划有关项目和经费管理办法，按要求认真填写《浙江省基础公益研究计划项目计划书》（简称《计划书》）。填写《计划书》时要求科学严谨、实事求是、表述清晰、准确，并认真阅读本填报说明。

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三、《计划书》经项目负责人和依托单位签字盖章，并经省自然科学基金委员会办公室审核批准后，将作为项目执行、检查、验收的依据。

四、资助项目的有关研究成果，包括论文、专著、专利、获奖等情况，均须按规定标注“浙江省基础公益研究计划项目”（属于省自然科学基金的可标注“浙江省自然科学基金项目”）和立项编号。

五、省基础公益研究计划的项目经费管理（包括省级财政拨款经费、联合资助经费、自筹经费）依照省财政关于科技项目的有关经费管理要求执行，非省级财政拨款单位联合资助经费参照执行。

基本信息

<table>
<tr><td rowspan="3">负责人信息</td><td>姓　名</td><td>方贵盛</td><td>性别</td><td>男</td><td>出生日期</td><td>1973-7-12</td></tr>
<tr><td>电 话</td><td>13606620840</td><td colspan="2">E-mail</td><td colspan="2">823180313@qq.com</td></tr>
<tr><td>证件类型</td><td>身份证 18 位</td><td colspan="2">证件号码</td><td colspan="2">362334197307121217</td></tr>
<tr><td rowspan="14">项目基本信息</td><td>项目名称</td><td colspan="5">基于仿尺蠖攀爬机器人的水闸钢丝绳在线激光清洗方法研究</td></tr>
<tr><td>英文名称</td><td colspan="5">Research on on-line laser cleaning method of sluice wire rope based on inchworm-like climbing robot</td></tr>
<tr><td>计划类别</td><td colspan="2">公益技术研究计划</td><td>项目类别</td><td colspan="2">工业</td></tr>
<tr><td>项目研究阶段</td><td colspan="5">应用研究</td></tr>
<tr><td>国家自然科学基金学科代码</td><td colspan="5">F030604</td></tr>
<tr><td>国家自然科学基金学科代码名称</td><td colspan="5">信息科学部/自动化/机器人学及机器人技术/微型机器人与特种机器人</td></tr>
<tr><td>国家标准学科分类与代码</td><td colspan="5">4605030</td></tr>
<tr><td>国家标准学科分类与代码名称</td><td colspan="5">机械工程/机械制造自动化/机器人技术</td></tr>
<tr><td>预计研究年限</td><td colspan="5">2021 年 1 月 至 2023 年 12 月</td></tr>
<tr><td>项目总经费</td><td colspan="2">10</td><td>其中省财政资助经费</td><td colspan="2">10 万元</td></tr>
<tr><td>中文关键词</td><td colspan="5">闸门钢丝绳；在线清洗；仿尺蠖机器人；激光清洗；刚柔耦合</td></tr>
<tr><td>英文关键词</td><td colspan="5">Steel wire rope of sluice; On-line cleaning; Inchworm-like robot; Laser cleaning; Rigid-flexible coupling</td></tr>
<tr><td colspan="6"></td></tr>
<tr><td colspan="6"></td></tr>
<tr><td>中文摘要</td><td colspan="6">项目研究内容与目标：
钢丝绳作为卷扬式启闭机中必不可少的连接件，是实现闸门提升最重要的组成部分，在整个水闸工程安全运行管理中起到举足轻重的作用。在不拆卸、不损伤基体情况下对闸门钢丝绳进行清洗养护是当前水闸工程安全管理中急需解决的技术难题。传统的人工清洗养护劳动强度大、劳动效率低，存在安全隐患与环境污染等问题，为此提出了一种采用仿尺蠖攀爬机器人携带激光清洗装置的水闸钢丝绳在线清洗方法。项目综合运用激光清洗原理与机器人-钢丝绳刚柔耦合动力学理论，采用仿真分析和实验验证方法，以激光清洗作业机理、激光清洗对钢丝绳的除污效果及可控性、风力与油污作用下激光清洗机器人攀爬稳定性、仿尺蠖攀爬机器人结构设计等科学问题和关键技术为突破口，采用 ANSYS、ADAMS 等仿真分析工具，解析机器人攀爬机制与污垢去除原理，设计激光清洗工艺流程，制作加工在线激光清洗机器人样机，进行激光在线清洗性能测试实验，并在省内多家水利设施运行管理部门进行应用推广，以实现水闸钢丝绳快速高效在线清洗，为浙江省水利行业实现“机器换人”，提升水闸钢丝绳养护水平与层次打下基础。</td></tr>
</table>

项目组成员

编号	姓名	成员类别	证件号码	性别	单位名称	电话
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5	王红梅	会员成员	420922197806198624	女	浙江水利水电学院	13958042396
6	钟建国	会员成员	330501198610102239	男	浙江水利水电学院	13655811405
7	张港	非会员成员	412829199704020014	男	浙江水利水电学院	0571-13513965986

项目经费

项目总经费 10 万元，其中省财政资助经费 10 万元（第一批财政拨款 10 万元，第二批财政拨款 0 万元），联合资助经费 0 万元，自筹经费 0 万元。

科研经费	名称	项目总经费预算（万元）
直接费用	1、设备费	0.00
	2、材料费	2.00
	3、测试化验加工费	2.00
	4、燃料动力费	0.00
	5、差旅费、会议费、合作、协作研究与交流费	1.50
	6、出版/文献/信息传播/知识产权事务费	1.00
	7、人员劳务费	1.50
	8、专家咨询费	0.50
间接费用	9、间接费用	1.50

需增添的仪器及设备：

无

研究计划

2021 年度
研究内容：在前期研究的基础上，继续完善项目整体解决方案。研究激光清洗水闸钢丝绳污垢机理，研究激光清洗水闸钢丝绳污垢工艺，研究激光清洗水闸钢丝绳对基体的影响及力学性能测试实验，进行机器人钢丝绳攀爬机理与结构设计，研究机器人-钢丝绳刚柔耦合动力学规律等。
研究目标：形成详细的项目研究解决方案，弄清楚激光清洗水闸钢丝绳污垢机理，获得可靠的激光清洗水闸钢丝绳污垢工艺参数；设计出钢丝绳攀爬机器人，掌握机器人-钢丝绳刚柔耦合动力学规律。本阶段结束后，拟申报专利 1 项，撰写论文 1 篇，出席国内外国际会议 1 次。

2022 年度
研究内容：对攀爬机器人控制系统进行研究设计，对风力作用与污垢环境下机器人攀爬稳定性进行研究，对激光清洗装置可控性进行研究。
研究目标：完成攀爬机器人主控制器的选型、驱动电机的选型与控制、机器人控制算法的设计、远程控制终端的设计、人机交互界面的设计；完成移动式激光清洗装置的设计，最终加工制作出一台激光在线清洗机器人样机。本阶段结束后，拟申报专利 1 项，撰写论文 1 篇，出席国内外国际会议 1 次。

2023 年度
研究内容：搭建水闸钢丝绳在线激光清洗实验平台，开展集成应用实验验证研究，包括激光清洗效果离线实验与在线实验，以及施工现场的性能测试实验，测试不同风力作用下和油污环境下机器人的综合性能参数等。
研究目标：通过实验验证与设计改进，所研究开发的激光在线清洗机器人样机在清洗速度、清洗效果、节能环保等方面均能满足水利部门的养护要求，最终实现投产，并在 3 家及以上单位得到推广应用。本阶段结束后，撰写论文 1 篇，总结项目研究成果，撰写项目研究报告，项目结题。

预期研究成果：

（1）应用示范：开发成功钢丝绳在线清洗养护机器人样机，并在 3 家及以上水闸运管单位得到应用推广。
（2）论文发表：凝练阶段性研究成果，在国内外重要期刊上发表论文 3 篇，其中 EI 或 SCI 收录论文 2 篇；申报专利 2 项，其中发明专利 1 项。
（3）人才培养：培养青年教师 1 名，联合培养研究生 1-2 名，本科生 4 名。
（4）预期经济社会效益：1）本项目所研究的技术与所开发的新产品，可以为浙江省乃至全国的水利行业解决水闸钢丝绳的清洗养护问题，代表了浙江省水利行业实现“机器换人”的发展方向，可以提升浙江省水闸钢丝绳的养护水平和层次。2）设备研制成功后，每台设备售价预计 10 万元左右，能够替代 2-3 个工人进行工作，每年可为每个闸站节省钢丝绳养护成本大约 0.5-1 万元，且不用承担安全风险、环境污染风险等。3）本项目具有完整的自主知识产权，有良好的成果转化价值。产品开发成功后，可以以注册公司或技术转让的方式为社会创造效益。4）该设备作为我校先进水利装备浙江省工程研究中心的主打研究产品，可以为社会和学校培养一批技术骨干，使他们成为省工程研究中心的中坚力量和技术的主要推广人员，促进浙江省水利事业的发展。

研究年限期间预期完成的成果：

一、预期成果产出情况								
论著	发表科技论文	3 篇	出版科技著作	0 部	共计出版科技专著：0 万字			
专利	发明专利申请	1 件	实用新型专利申请	1 件	发明专利授权	1 件	实用新型专利授权	1 件
技术标准	国际标准	0 项	国家标准	0 项	行业标准	0 项		
	地方标准	0 项	企业标准	0 项				
二、本课题预期人才培养情况								
研究期限内项目组成员晋升职称人数：0				研究期限内参与本项目的毕业研究生人数：1				
三、预期成果转化情况								
是否能实现成果转化：　能转化								
成果转化形式	新产品	1 项	新工艺	0 项	新技术	0 项	新品种	0 项
	开创性的产品或技术：水闸钢丝绳在线激光清洗机器人							
	替代国外进口的产品或技术：无							
经济效益	提升销售	0 万元，测算依据：请填写						
	产生利税	0 万元，测算依据：请填写						
环境治理	节能	否	节水	是	减排废气	否		
	减排废物	否	减排废水	是				
治理	对公共卫生起到明显提升作用：否			对公共安全起到明显提升作用：否				

能力	对社会治理起到明显提升作用：否	对防灾减灾起到明显提升作用：否

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我接受浙江省基础公益研究计划的资助，将按照项目申请书、批准通知和计划书负责实施本项目，严格遵守浙江省基础公益研究计划相关项目和经费管理规定，切实保证研究工作时间，认真开展研究工作，按时报送有关材料，及时报告重大情况变动，对资助项目发表的论著和取得的研究成果按规定进行标注。

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2020年12月28日

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Design and Implementation of a Wire Rope Climbing Robot for Sluices

Guisheng Fang [1,*] and Jinfeng Cheng [1,2]

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Keywords: climbing robot; mechanical analysis; spring clamping; sluice gate; wire rope; wheeled movement

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1. Introduction

In water conservancy engineering facilities, sluice gates are widely used in rural and coastal river channels as the main water retaining and discharge structures. As the main load-bearing component of the hoisting sluice, the wire rope plays a vital role in the safe operation of the sluice. Due to the long-term exposure of the sluice wire rope to the outdoors, it is affected by irregular bearing, wind, rain, and sun, which will lead to various problems, such as grease hardening, local corrosion, wear, and breakage. Therefore, regular maintenance is essential for the proper operation of the wire rope. Currently, most of the daily maintenance of the sluice wire rope is done manually, leading to problems, such as high labor cost and intensity, low work efficiency, and high-risk factor. With the application of the scientific and technological developments in the field of robotics to the daily maintenance process of the wire rope, the above-mentioned problems can be easily solved. Therefore, the research and development of a wire rope climbing and maintenance robot in the water conservancy industry are anticipated to significantly improve work efficiency in this field, successfully addressing the labor issue in enterprises.

As an important branch of the mobile robot family, climbing robots have received widespread attention from the scientific community in the past two decades. As a result, a wide variety of prototype systems have been developed for specific applications, such as steel bridge climbing robots [1–4], cable-climbing robots [5–8], pole-climbing robots [9–13], tree-climbing robots [14–17], pipe-climbing robots [18,19], wall-climbing robots [20–24], among others.

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Article

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In terms of rope-climbing robots, Koo et al. [25] developed a climbing robot based on the piston mechanism for a robotic competition in Malaysia. The robot consisted of a base frame and two clampers. The two clampers were used to grip the rope, and the base frame based on the piston mechanism was utilized to realize the climbing motion. The advantages of the proposed robot are low energy consumption, low cost, and ease to control and build. However, the robot is unable to climb vertically fixed ropes. When the robot is in action, it will occasionally cause vibration along the rope.

Cho et al. [26–28] designed three climbing and detection robots for hanger cables of suspension bridges, named WRC^2IN-I, WRC^2IN-I+, and WRC^2IN-II. WRC^2IN-I was composed of a wheel drive mechanism, an attachment mechanism, and a safe landing mechanism. It could climb at 50 mm/s under the condition of a 15 kg load. However, when the wheeled cable-climbing robot moved on the uneven cable surface, it would produce periodic vibration, which would affect the detection quality. Therefore, the project team improved the first-generation cable climbing robot by changing the wheeled structure into a tracked structure, which greatly reduced the vibration. In order to further simplify the installation and disassembly process of the first-generation robot and improve work efficiency, the project team developed the second-generation cable climbing robot named WRC^2IN-II. The robot was composed of two separable attachment modules, two driving modules, and two obstacle-surmounting sub-modules. After improvement, the robot could carry a load of 24 kg, while the installation and disassembly time only took about 5 min. Although these robots are all able to climb vertically fixed wire ropes, their dimensions are large and the applicable cable diameters are 50–90 mm.

Sun, G. [29] designed a wire rope climbing robot for the detection needs of lamps on the top of airport lighting streetlights. The robot was composed of a compression mechanism, a suspension mechanism, and a tracked type moving mechanism. The climbing robot could maneuver on a wire cable with a cross-sectional diameter varying from 10 to 14 cm with a stable and secure speed of 1 m/s. It could also lift up to 58 kg with respect to its own weight of 15.6 kg.

Ratanghayra, P. R. [30] designed a simple climbing robot for soft ropes. The robot was composed of a mounting frame and four mutually staggered wheels with motors. The wheels were pressed against the rope by the action of springs, and could adapt to the climbing tasks on ropes of different diameters. For hard wire ropes, the climbing performance of the robot will be greatly reduced.

Fang, G. [31] developed a pneumatic wire rope climbing robot, WRR-I, for the maintenance of sluice wire ropes. The robot adopted a split structure, which was composed of an upper device and a lower device. The pneumatic drive cylinder was used to realize the robot's clamping, moving, and guiding functions. Moreover, it could carry a camera and a laser cleaning device to detect and clean the sluice wire rope. The disadvantage of the robot is that its motion is discontinuous.

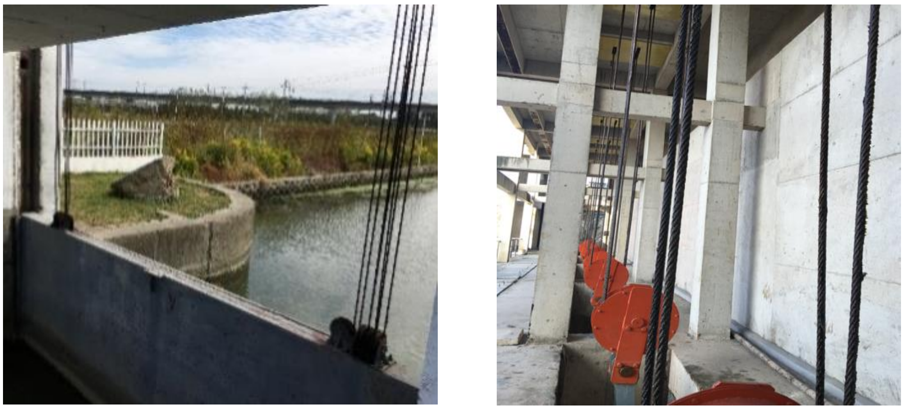
Under this direction, this work was mainly focused on the description of a wheeled type rope climbing robot for sluices, which was applied to carry laser cleaning and testing equipment, as well as other working tools to carry out daily maintenance of the wire rope. Therefore, the service life of the sluice wire rope can be prolonged.

The rest of this work is organized as follows. In Section 2 some considerations on robot design are analyzed, while in Section 3 the mechanical structure of the six-wheeled wire rope climbing robot is presented. In Sections 4–6, the mechanical analysis of the robot is established and verified by experiments. Finally, in Section 7 the conclusions and future work are discussed.

2. Considerations on Robot Design

Different regions and different types of hoisting sluices employ different diameters and lengths of wire ropes. For example, the sluice used in rural river channels (as the example shown in Figure 1a) uses a wire rope with a diameter of about 10–20 mm, and a length of about 5–8 m, while the sluice used in coastal rivers (as the example depicted in

Figure 1b) uses a wire rope with a diameter of about 15–30 mm, and a length about 6–15 m. By considering its versatility, the goal of the designed robot is to be able to adapt to sluice wire rope climbing tasks with diameters in the range of 10–30 mm and lengths in the range of 5–15 m.



(**a**) (**b**)

Figure 1. Sluice and wire rope working scene. (**a**) An example of the sluice used in rural river channels, and (**b**) an example of the sluice used in coastal rivers.

Differently from straight rods, wire ropes are spirally wound with multiple strands of steel wire, causing the surface of the wire rope to be uneven and flexible. Due to the long-term operation of the wire rope, its surface will have problems, such as grease hardening, broken wire, corrosion, wear, and looseness, which can effectively lead to certain changes in the diameter of the wire rope. This fact requires the designed climbing robot to have the ability to adapt to different environments, and also to overcome obstacles. According to observation, it is generally required that the robot's obstacle-crossing height should be $\geq$2 mm.

Most of the sluice wire ropes are installed vertically, and their working states are either tensioned or relaxed. While in tension, the inclination angle of the wire rope is generally 80–90°. Hence, the robot should be able to climb up and down with a load in both vertical and inclined directions, not causing damage to the wire rope. It is important to point out the fact that the sluice is hoisted by multi-strand wire ropes, through dynamic and static pulleys. The wire rope of each hanging point on the gate is arranged in four or more strands, and the distance between the two strands of wire rope is different (generally in the range of 50–300 mm). This requires that the size of the lateral structure of the designed robot should not exceed 150 mm. The wire rope is coated with grease, while the degree of hardening varies with the working time, which results in a small dynamic and static friction coefficient between the robot and the wire rope contact surface. The robot needs to be equipped with detection devices, cleaning devices, and oiling devices, which are important for maintenance operations. Thus, the weight of the robot itself should not be more than 6 kg. At the same time, to can carry work tools, the load capacity of the robot needs to be higher than 3 kg. Compared with manual maintenance, robot operation requires a certain performance improvement. Therefore, it needs to have a certain climbing operation speed, which should be $\geq$20 mm/s with a 3 kg load, and $\geq$30 mm/s without a load. In addition, to ensure the continuity of maintenance operations, the robot requires good climbing stability, with no sudden change in acceleration under normal conditions. On top of that, climbing robots work during high-altitude operations, leading to the necessity of ensuring their safety in the event of a power outage, in order that they will not slip and fall on these occasions. Another factor to be considered is that the robot needs to clean multiple wire ropes. In order to improve work efficiency and reduce non-working time, it is required that installation and disassembly are simple and convenient.

Based on the above-mentioned considerations, the designed climbing robot for sluice wire rope should meet the design requirements shown in Table 1.

Table 1. Design requirements of the climbing robot for the sluice wire rope.

Dimensions (L × W × H)	≤250 × 150 × 400 mm
Weight	≤6 kg
Load capacity	≥3 kg
Adaptable diameter	φ10–30 mm
Climbing speed	≥20 mm/s (with a 3 kg load); ≥30 mm/s (without a load)
Obstacle-crossing ability	≥2 mm
Installation time	≤5 min

3. Mechanism Design

3.1. Choice of the Attachment and Locomotion Methods

According to the above-mentioned analysis, the key factors to be considered in the design of the climbing robot for sluice wire rope are the choice of attachment method and the locomotion method. There are also other important considerations, which include power loss safety and flexibility of the wire rope, among others.

(1) The choice of the attachment method. Although the wire rope is a magnetically conductive material, the surface of the wire rope is both oily and uneven, which significantly attenuates its magnetic adsorption force. Hence, it can be concluded that the magnetic adsorption method is incompetent. Due to the uneven surface of the wire rope, both the clamping attachment and claw-thorn attachment methods can be applied. Compared with the claw-thorn grasping method, the clamping attachment method is simpler in structure and more adjustable in strength. For this reason, this method was chosen to be adopted for the proposed design. In terms of the selection of the specific clamping methods, two forms were considered in an earlier stage, namely, pneumatic clamping and electric clamping. After experimental verification, it was found that although the clamping force of the pneumatic clamping is large, the pneumatic control is more complex, and additional assistance, such as an air pump, is required. Besides, the electric gripping requires motors or electromagnets, resulting in excessive weight of the robot. The spring clamping method has the characteristics of adjustable clamping force, simple structure, and low cost, thus for this design, the spring clamping method was adopted.

(2) The choice of the locomotion method. For wire rope climbing, wheeled, legged, crawler, and telescopic methods can all meet the design requirements. Due to the complex control and slow speed of the legged and telescopic climbing robots, they were not considered for this design. Compared with the wheeled climbing robot, the crawler-type climbing robot needs to be specially designed in order to obtain stable vertical climbing performance on the oily wire rope, increasing the entire design cost. The wheeled robot is simple in structure, and convenient to manufacture. Thus, for the introduced design the wheeled climbing and moving method was adopted. In order to reduce the influence of the clamping mechanism on the extrusion and deformation of the wheels, a six-wheel climbing method was also adopted.

(3) Other considerations. Due to the small diameter of the sluice wire rope and the small distance between the two wire ropes, the commonly used prismatic frame structure and cylindrical frame structure equipped with three moving modules were considered as not suitable. Therefore, for the proposed design, a cuboid frame structure equipped with two moving modules was adopted. The structure has a narrow width, which is convenient for the installation and disassembly of the robot, and will also not collide and interfere with the wire rope. In terms of power loss safety considerations, the robot is driven by a DC planetary gear reduction motor. In the event of power loss, the motor has a good

locked-rotor performance, which can prevent the robot from slipping off the wire rope when it loses power.

3.2. Overall Structure Design of a Wheeled-Climbing Robot for Sluice Wire Rope

According to the aforementioned design requirements, as well as the scheme analysis, a six-wheel climbing robot for sluice wire rope named WRR-II (the second generation of wire rope climbing robot) was developed. The robot was composed of two detachable frames: a left frame composed of a driving trolley, a control box, and an upper anti-deflection guide device. The right frame is composed of a driven trolley, a trolley position adjustment mechanism, and a lower anti-deflection guide device.

The backs of the left and right frames were connected by hinges, in order that they can be easily opened and fixed onto the wire rope. The front parts of the left and right frames were clamped by pull buckles to form a closed robot, to prevent the robot from being detached from the wire rope when it is working. The control box, which was used to perform remote control operations, was equipped with several components, such as a DC power supply, a motor drive unit, a wireless control unit, etc. The upper and lower anti-deviation guide devices were composed of four mounting frames and four rollers, which play the role of anti-deviation and guidance when the robot is climbing, preventing the robot from detaching from the wire rope. Additionally, there are installation holes on the upper and lower parts of the left and right frames, which can be equipped with inspection, cleaning, oiling, and other equipment to carry out maintenance operations on the wire rope. The schematic diagram of the two- and three-dimensional structures of the designed robot is shown in Figure 2.

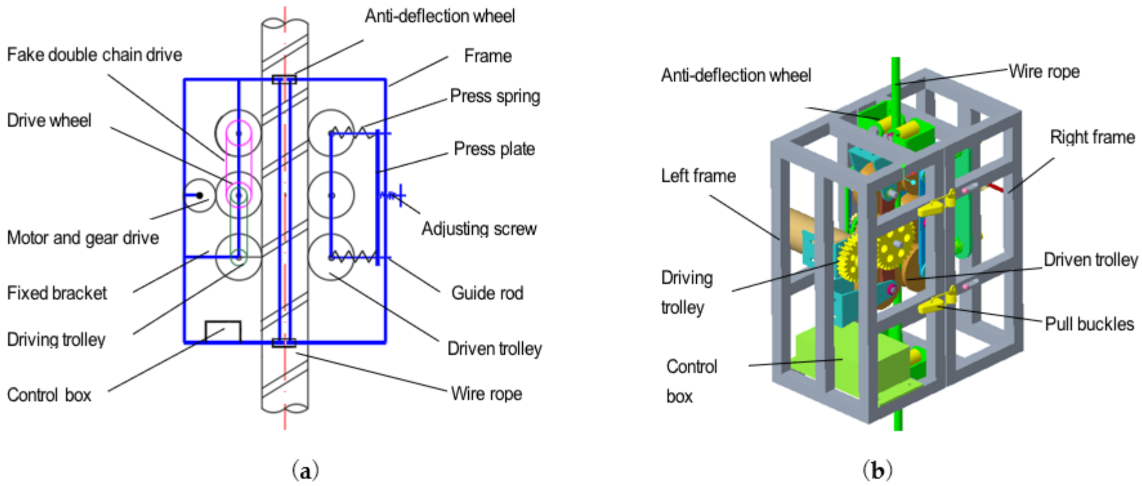
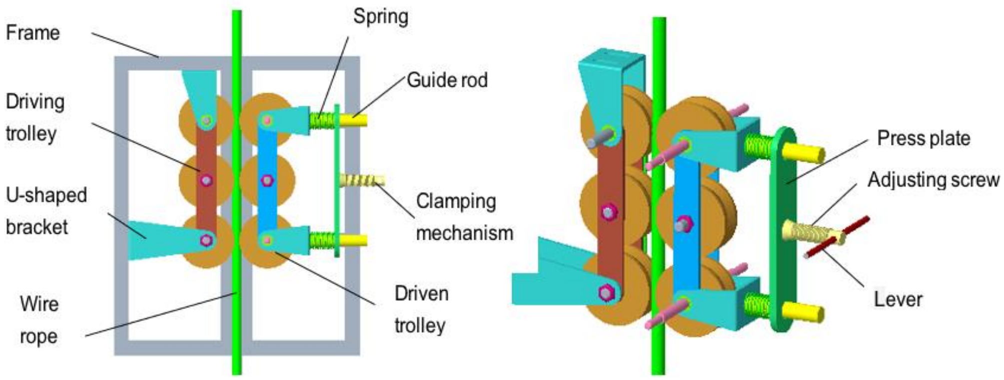


Figure 2. Wheeled climbing robot for wire rope for the sluice. (**a**) 2D schematic diagram of the robot, and (**b**) 3D CAD structure of the robot.

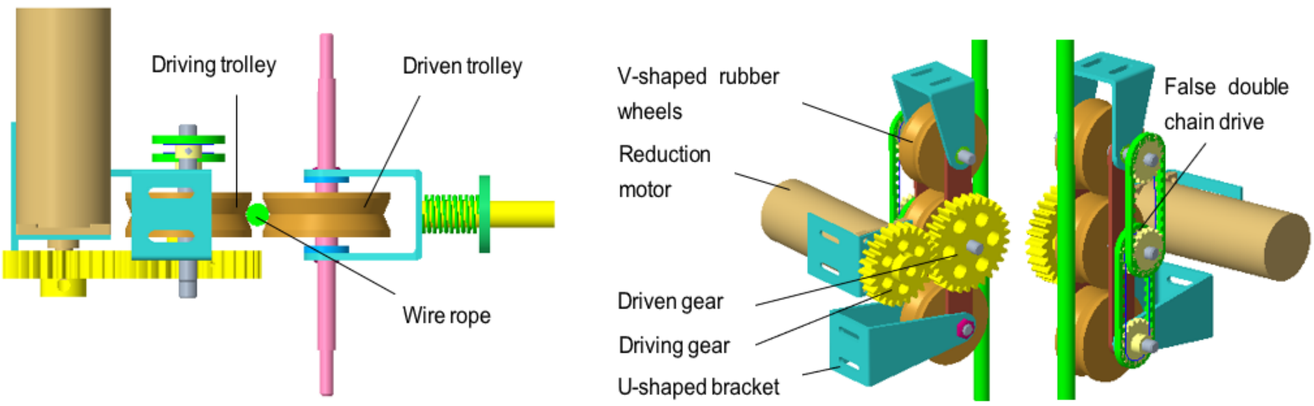
(1) Robot attachment device. The entire attachment device was clamped by the left-driving trolley and the right-driven trolley through the compression spring, to clamp the wire rope and its three-dimensional structure, as illustrated in Figure 3. The left-driving trolley was fixed on the left frame through the U-shaped bracket, while the position of the right driven trolley within the right frame can be adjusted through the upper and lower guide rods. When the left and right frames are enclosed, the left and right trolleys clamp the wire rope through the V-shaped rubber wheels, where the clamping force can be adjusted by manual levers, by adjusting screws, pressing plates, and springs. In order to reduce the influence of the clamping force on the deformation of the rubber wheel and the wire rope, and increase the contact area between the wheel and the wire rope, the left and right trolleys were equipped with three V-shaped rubber wheels on each wheel frame. The V-shaped rubber wheel also presents good contact and guiding effect with the wire rope.



(**a**) (**b**)

Figure 3. The 3D CAD structure of the attachment device. (**a**) The external frame of the attachment device, and (**b**) the internal structure of the attachment device.

(2) Robot locomotion device. The locomotion device consists of a left-driving trolley and a right-driven trolley, as depicted in Figure 4. The left-driving trolley was composed of a DC reduction motor, a gear pair, three V-shaped rubber wheels, L-shaped and U-shaped fixed brackets, axles, bearings, wheel lateral mounting plates, and false double chain drive mechanisms. The geared motor was fixed onto the left frame by an L-shaped bracket, while the driving gear was installed coaxially with the motor. The driven gear and the intermediate driving wheel were fixed together by the axle, and the three V-shaped wheels were fixed onto the left frame through the wheel axle, the wheel frame, and the upper and lower U-shaped frames. A transmission sprocket was also installed onto the outside of each of the three axles, while each driving sprocket was fixed with the wheel axle through a locking screw. When the motor rotates, it drives the driving gear and the driven gear, thus the middle driving wheel rotates. When the middle driving wheel rotates, the upper and lower driving wheels also rotate by the action of the false double-row chain transmission. Thereby, the robot can climb up and down through the friction between the driving wheel and the wire rope. The geared motor has a reverse self-locking function, which can ensure that it does not rotate in a power-off state, thereby preventing the robot from falling. The right-driven trolley is composed of three V-shaped rubber wheels, two U-shaped fixed frames, three wheel axles, bearings, and wheel-side mounting plates. The three V-shaped wheels of the driven trolley are driven wheels, which mainly play the role of auxiliary guidance and support when the robot is running.



(**a**) (**b**) (**c**)

Figure 4. The 3D CAD structure of the locomotion device. (**a**) The top view of the mobile device, (**b**) the front structure of the driving trolley, and (**c**) the back structure of the driving trolley.

4. Mechanical Analysis

Mechanical analysis is mainly used to determine the pressing force of the robot, as well as the driving torque and several structural parameters of the motor, to provide a theoretical basis for the optimization of the robot mechanism, the selection of the motor, and the motion control. The designed robot in this work belongs to a redundant statically indeterminate structure, with a relatively complex mechanical analysis. In order to simplify its mechanical analysis process, the following assumptions were made:

(1) The wire rope is fixed at both the top and bottom, and the tensile force at both ends is large enough, and therefore, the wire rope can be regarded as an approximate rigid body. The wire rope is also inelastically elongated.

(2) During the climbing process of the robot, the wheels only roll and do not slide.

(3) The front and back sections, as well as the left and right sections, of the robot are symmetrical, with the center of mass coinciding with the origin O′ of the robot's local coordinate system, which is located at the intersection of the line that connects the centers of wheel 3 and wheel 4 and the axis of the wire rope.

(4) The stiffness coefficients of the two compression springs are the same, which are also equal to the compression lengths.

(5) In the pressed state, the wheel does not deform.

4.1. Static Analysis

4.1.1. Static Analysis of the Hovering State

In order to analyze the balance and driving conditions of the robot, a schematic diagram of the force analysis in the hovering state of the robot is established, as shown in Figure 5. In the figure, YOZ is the inertial coordinate system, Y′O′Z′ is the local coordinate system of the robot, O and O′ are their coordinate origins, F_I refers to the clamping force acting on each V-shaped wheel, N_I denotes the normal force of the wire rope to each wheel, F_{fi} represents the friction force between the wheel and the wire rope, G stands for the total weight of the robot together with the load, θ is the angle between the axle of the wire rope and the Y direction of the inertial coordinate system, F signifies the clamping force applied at the handle, k is the stiffness coefficient of the spring, r is the radius of the wire rope, R denotes the radius of the V-shaped wheel, and L is the distance between the two wheels along the axis of the wire rope.

According to the force balance equations, Equations (1) and (2) can be obtained.

$$\sum Y' = 0,\ F_1 + F_3 + F_5 + N_2 + N_4 + N_6 + G\cos\theta - F_2 - F_4 - F_6 - N_1 - N_3 - N_5 = 0 \quad (1)$$

$$\sum Z' = 0,\ F_{f1} + F_{f3} + F_{f5} + F_{f2} + F_{f4} + F_{f6} - G\sin\theta = 0 \quad (2)$$

By considering that the structure of each wheel is symmetrical and the load is balanced, then Equations (3)–(7) can be obtained.

$$N_1 = N_3 = N_5 \quad (3)$$

$$N_2 = N_4 = N_6 \quad (4)$$

$$F_1 = F_3 = F_5 \quad (5)$$

$$F_2 = F_4 = F_6 \quad (6)$$

$$F_{fi} = \mu N_I,\ i = 1 \sim 6 \quad (7)$$

In Equation (7), N_I is the normal force of the wire rope to each wheel, and μ represents the static friction coefficient between the wheel and the wire rope.

In the hover state and since $F_1 = F_2$, the values of N_1 and N_2 can be determined by Equations (8) and (9).

$$N_1 = \frac{G\sin\theta}{6\mu} + \frac{G\cos\theta}{6} \quad (8)$$

$$N_2 = \frac{G\sin\theta}{6\mu} - \frac{G\cos\theta}{6} \quad (9)$$

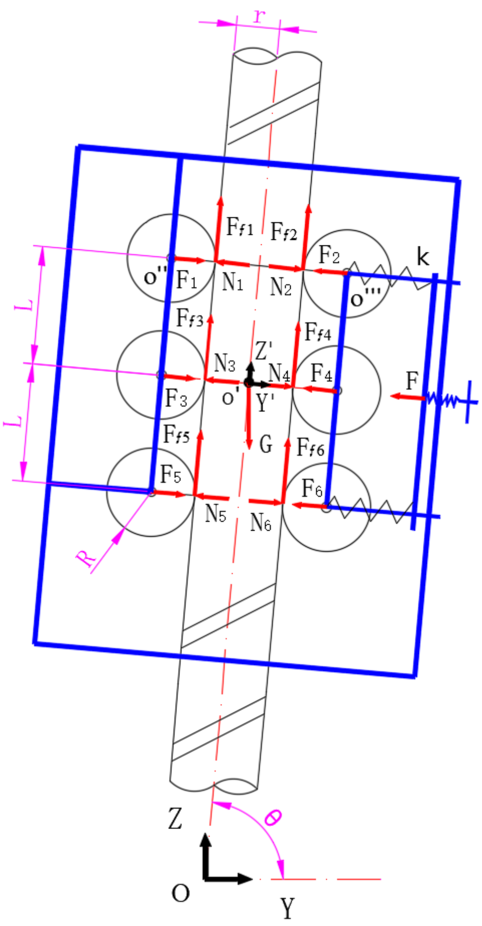


Figure 5. Force diagram of the robot in the YOZ coordinate plate.

According to the force analysis of wheel 1, Equations (10) and (11) can be obtained.

$$N_1 = F_1 + \frac{G}{3}\cos\theta \quad (10)$$

$$F_1 = N_1 - \frac{G\cos\theta}{3} = \frac{G\sin\theta}{6\mu} - \frac{G\cos\theta}{6} \quad (11)$$

The clamping force F can be expressed by Equation (12).

$$F = F_1 + F_3 + F_5 = F_2 + F_4 + F_6 = 3\,F_1 \quad (12)$$

By combining Equation (11) with Equation (12), the following is obtained:

$$F = \frac{G\sin\theta}{2\mu} - \frac{G\cos\theta}{2} \quad (13)$$

For the robot to be able to hover on the wire rope, the clamping force F applied at its handle should satisfy the following condition:

$$F \geq \frac{G\sin\theta}{2\mu} - \frac{G\cos\theta}{2} \quad (14)$$

By substituting the basic parameters of the robot as follows: $G = 40\ N$, $\mu = 0.1$, $\theta = 90°$, $k = 50\ N/cm$, the minimum value of the clamping force F is the following:

$$F \geq 200\ N \tag{15}$$

According to Hooke's law $F = 2k\Delta x$, the minimum distance that the screw needs to move can be determined by Equation (16).

$$\Delta x = \frac{F}{2k} = \frac{200}{2 \times 50} = 2\ cm \tag{16}$$

4.1.2. Static Analysis When the Robot Has an Upward Movement Trend

When driving wheel 1 of the robot rotates clockwise, the robot tends to move upward, and its force analysis is displayed in Figure 6a. At this point, the friction of the left wheel is upward, and the friction of the right wheel is downward. By considering the symmetry of the three pairs of left and right wheels, and in order to simplify the calculation process, the force analysis of the entire robot was considered equivalent to the force analysis of the top pair of wheels, as shown in Figure 6b.

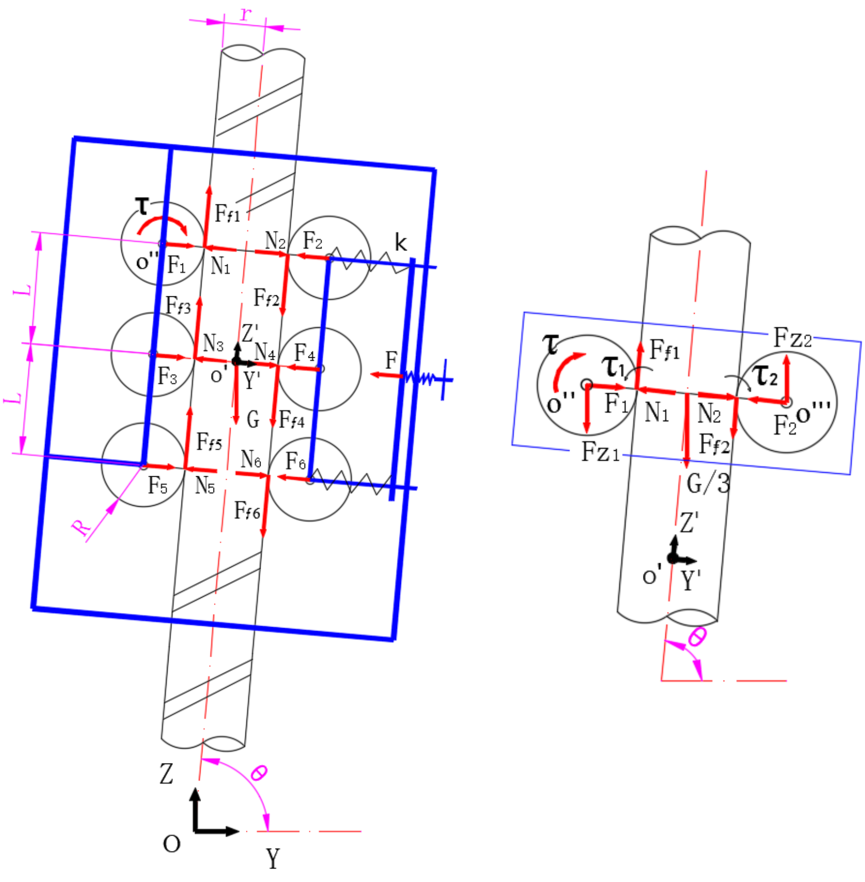


Figure 6. Force diagram of the robot when it has an upward movement trend. (**a**) Force diagram in the YOZ coordinate plane, (**b**) simplified equivalent force diagram.

According to the force and moment equilibrium conditions, and assuming that the weight of the wheel is negligible, the following balance equations can be established.

$$\sum Y' = 0,\ F_1 + N_2 + \frac{G}{3}\cos\theta - F_2 - N_1 = 0 \tag{17}$$

$$\sum Z' = 0,\ F_{f1} - F_{f2} - \frac{G}{3}\sin\theta = 0 \tag{18}$$

$$\sum M_{o''} = 0,\ F_{f1}R - F_{f2}(R + 2r) - \frac{G}{3}\sin\theta(R + r) - \tau_1 - \tau_2 = 0 \tag{19}$$

where O'' is the center of mass of wheel 1, O''' stands for the center of mass of wheel 2, R is the radius of the wheel, r is the radius of the wire rope, and τ_1,τ_2 denote the rolling friction couple moments of wheel 1 and wheel 2, respectively.

In the previous three equations, there are seven unknown values. Hence, the left and right wheels, as well as the robot framework, need to be solved separately. The force diagrams are shown in Figure 6b.

The balance Equations (20)–(22) can be obtained from wheel 1.

$$\sum M_{o''} = 0,\ F_{f1}R = \tau_1 \tag{20}$$

$$\sum Y' = 0,\ N_1 = F_1 + F_{z1}\cos\theta \tag{21}$$

$$\sum Z' = 0,\ F_{f1} = F_{z1}\sin\theta \tag{22}$$

The balance Equations (23)–(25) can be obtained from wheel 2.

$$\sum M_{o'''} = 0,\ F_{f2}R = \tau_2 \tag{23}$$

$$\sum Y' = 0,\ N_2 = F_2 \tag{24}$$

$$\sum Z' = 0,\ F_{f2} = F_{z2} \tag{25}$$

The balance Equations (26)–(27) can be obtained from the robot framework.

$$\sum Y' = 0,\ F_1 + F_{z1}\cos\theta = F_2 \tag{26}$$

$$\sum Z' = 0,\ F_{z1}\sin\theta = F_{z2} + \frac{G}{3}\sin\theta \tag{27}$$

When the wheel is in a critical equilibrium state, the rolling friction couple moment reaches the maximum value, which is equal to the following:

$$\tau_1 = \delta N_1 \tag{28}$$

$$\tau_2 = \delta N_2 \tag{29}$$

where N_i is the normal force of the wire rope to each wheel, and δ is the rolling friction coefficient between the wheel and the wire rope.

By combining Equations (17)–(29), the following can be obtained:

$$\boldsymbol{\tau} \geq 3F_{f1}R = 3F_{f2}(R + 2r) + G\sin\theta(R + r) + 3\tau_1 + 3\tau_2 = 9\delta F_2 + 6\delta F_2\frac{r}{R} + G\sin\theta(R + r) \tag{30}$$

By also considering that $F_2 = \frac{F}{3}$:

$$\boldsymbol{\tau} \geq 3\delta F + 2\delta F\frac{r}{R} + G\sin\theta(R + r) \tag{31}$$

Substituting the basic parameters of the robot as: G = 40 N, δ = 2 mm, θ = 90°, R = 26 mm, r = 5 mm, and F = 300 N, the minimum value of the drive torque τ is the following:

$$\boldsymbol{\tau} \geq\ 3.27\ \text{n.m} \tag{32}$$

4.1.3. Static Analysis When the Robot Has a Downward Movement Trend

When driving, wheel 1 of the robot rotates counterclockwise and the robot tends to move downward—its force analysis is displayed in Figure 7a. At this point, the friction of the left wheel is downward, and the friction of the right wheel is upward. By considering the symmetry of the three pairs of left and right wheels, and in order to simplify the calculation process, the force analysis of the entire robot is considered equivalent to the force analysis of the top pair of wheels, as illustrated in Figure 7b.

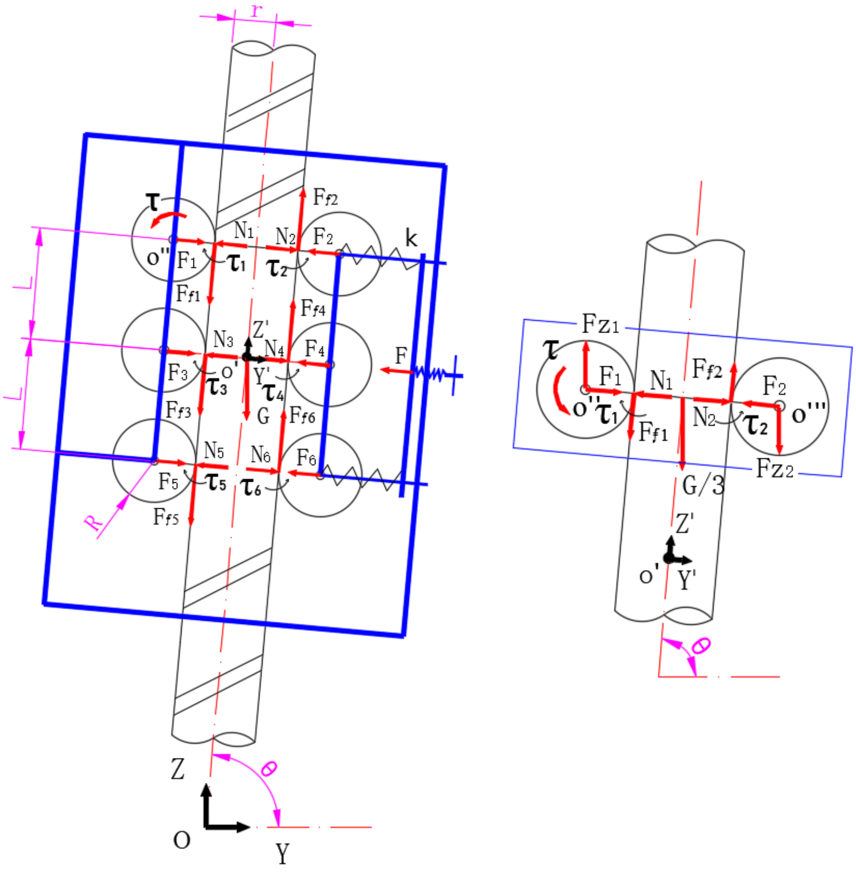


Figure 7. Force diagram of the robot when it has a downward movement trend. (**a**) Force diagram in the YOZ coordinate plane, (**b**) simplified equivalent force diagram.

According to the force and moment balance conditions, and assuming that the weight of the wheel is negligible, the following equilibrium equations can be established.

$$\sum Y' = 0,\ F_1 + N_2 + \frac{G}{3}\cos\theta - F_2 - N_1 = 0 \tag{33}$$

$$\sum Z' = 0,\ F_{f2} - F_{f1} - \frac{G}{3}\sin\theta = 0 \tag{34}$$

$$\sum M_{o''} = 0,\quad -F_{f1}R + F_{f2}(R+2r) - \frac{G}{3}\sin\theta(R+r) - \tau_1 - \tau_2 = 0 \tag{35}$$

Similar to the solving method of forces for the upward motion trend of the robot, the left and right wheels and the frame were taken as research objects, and the force diagrams are shown in Figure 7b. The equilibrium equation was solved, and the following was obtained:

$$\boldsymbol{\tau} \geq 3\delta F + 2\delta F\frac{r}{R} - G\sin\theta(R+r) \tag{36}$$

By substituting the basic parameters of the robot as follows: $G = 40$ N, $\delta = 2$ mm, $\theta = 90°$, $R = 26$ mm, $r = 5$ mm, and $F = 300$ N, the minimum value of the drive torque τ is the following:

$$\boldsymbol{\tau} \geq 0.79 \text{ n.m} \tag{37}$$

4.2. Kinematics Analysis of the Robot

The schematic diagram of the kinematics analysis of the robot is shown in Figure 8.

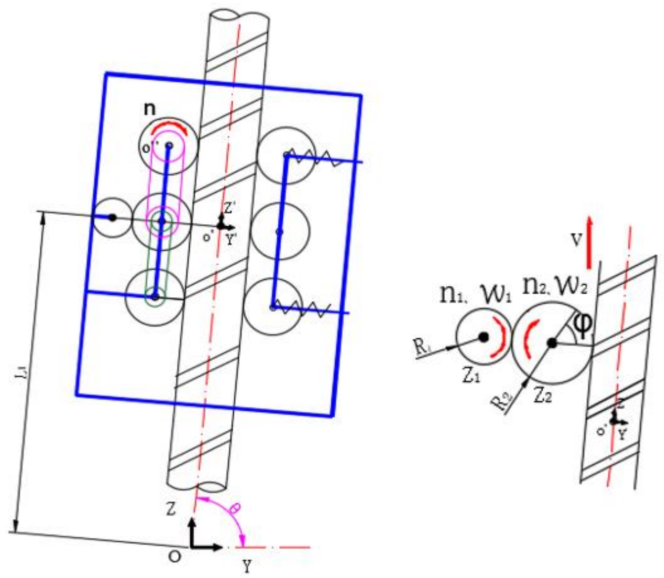


Figure 8. Schematic diagram of the kinematics analysis of the robot.

In Figure 8, L_1 is the initial position length of the robot on the wire rope, v refers to the climbing speed of the robot, n_1 is the rotation speed of the motor, n_2 is the rotation speed of the driving wheel, Z_1 denotes the number of teeth of gear 1, Z_2 is the number of teeth of gear 2, w_1 represents the rotational angular velocity of the motor, w_2 is the rotational angular velocity of the driving wheel, φ stands for the rotational angle of the driving wheel, and θ is the angle between the axle of the wire rope and the Y direction of the inertial coordinate system.

The position equation of the robot can be expressed by Equation (38).

$$\begin{cases} y = L_1\cos\theta + \varphi R_2\cos\theta \\ z = L_1\sin\theta + \varphi R_2\sin\theta \end{cases} \tag{38}$$

The speed formula of the gear transmission pairs can be expressed by the following expression:

$$\frac{n_1}{n_2} = \frac{Z_2}{Z_1} \tag{39}$$

The rotation angle φ of driving wheel 1 can be calculated as follows:

$$\varphi = w_2 t = \frac{2\pi n_2}{60}t = \frac{\pi n_2}{30}t = \frac{\pi Z_1 n_1}{30Z_2}t \tag{40}$$

According to Equation (38) and Equation (40), the position equation of the robot can be obtained as the following:

$$\begin{cases} y = L_1\cos\theta + \frac{\pi Z_1 n_1}{30Z_2}R_2 t\cos\theta \\ z = L_1\sin\theta + \frac{\pi Z_1 n_1}{30Z_2}R_2 t\sin\theta \end{cases} \tag{41}$$

The velocity equation of the robot can be obtained as follows:

$$\begin{cases} v_y = \dot{y} = \dot{\varphi}R_2\cos\theta = w_2R_2\cos\theta = \frac{\pi Z_1 n_1}{30Z_2}R_2\cos\theta \\ v_z = \dot{z} = \dot{\varphi}R_2\sin\theta = w_2R_2\sin\theta = \frac{\pi Z_1 n_1}{30Z_2}R_2\sin\theta \end{cases} \tag{42}$$

The acceleration equation of the robot is obtained as the following:

$$\begin{cases} a_y = \ddot{y} = \ddot{\varphi}R_2\cos\theta = \dot{w}_2R_2\cos\theta \\ a_z = \ddot{z} = \ddot{\varphi}R_2\sin\theta = \dot{w}_2R_2\sin\theta \end{cases} \tag{43}$$

By substituting the basic parameters of the robot as follows: $Z_1 = 25$, $Z_2 = 30$, $\theta = 90°$, $R_2 = 26$ mm, and $n_1 = 23$ r/min, the theoretical value of the climbing speed of the robot is the following:

$$v_z = 52\ \mathrm{mm/s},\ v_y = 0\ \mathrm{mm/s} \tag{44}$$

5. Control Architecture

The current climbing robot can carry cameras and NDT equipment to detect defects in wire ropes. The electronic architecture of the WRR-II platform is presented in Figure 9. The hardware control box is depicted in Figure 10. The control system consists of two main components, namely, the user-level controller and the low-level controller. The user-level controller is on the Tablet PC platform, and it provides the user interface and data transmission from the climbing robot. The low-level controller is based on the STM32F407ZET6 main control unit (MCU), which controls the motion of the DC motors and the peripheral devices (surveillance camera, extended NDT device, etc.). The communication between the two levels was set through a Wi-Fi module. The user interface (UI) was developed based on Qt software. The robot was instructed to move upward and downward by the UI. In order to reduce the weight of the robot, the power supply was provided from the external module in our current system.

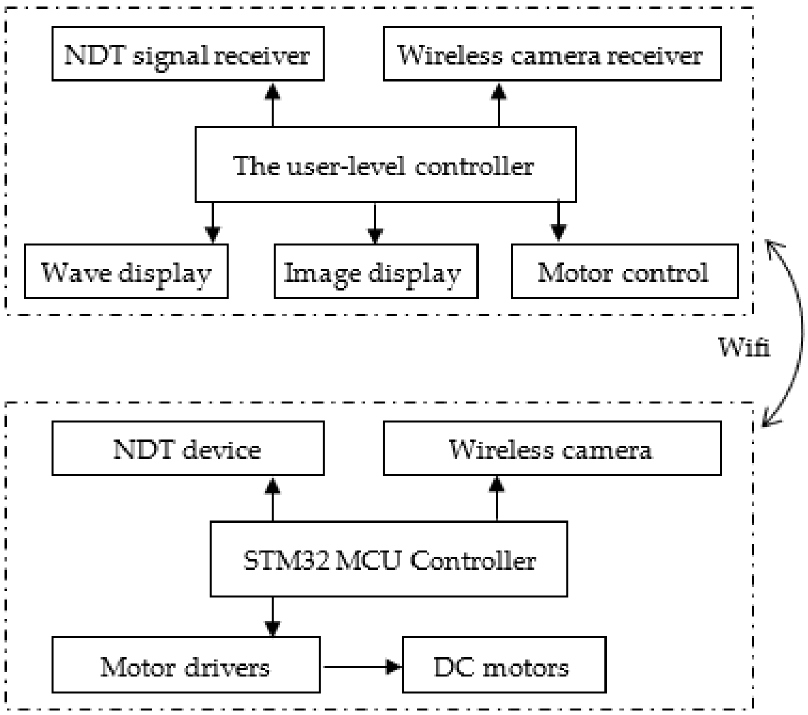


Figure 9. The control architecture of WRR-II.

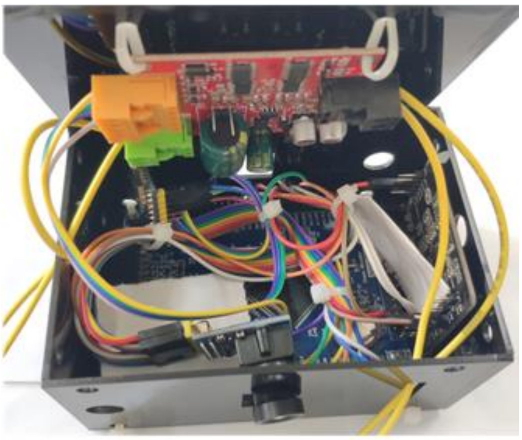
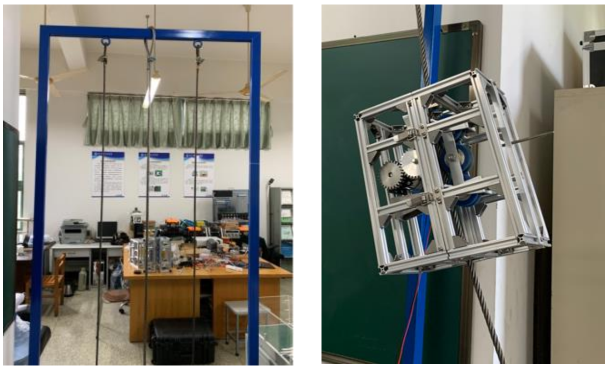


Figure 10. The control box of WRR-II.

6. Experiments

In order to verify the rationality of both the design scheme and the mechanical analysis of the robot, a prototype robot was built (WRR-II), as shown in Figure 11. In order to reduce the weight, except for the DC motor, chain drive mechanism, and V-shaped rubber wheel, the rest of the robot is made of aluminum alloy. The total mass of the robot is 3.8 kg, and the structural size of the robot is 250 × 150 × 300 mm (L × W × H).



(**a**) (**b**)

Figure 11. Experimental verification of the robot. (**a**) The experimental gantry, and (**b**) the climbing robot fixed on the gantry.

In order to simulate the working scene of the outdoor sluice, an experimental gantry with a height of 2 m and a width of 1.2 m was built, as illustrated in Figure 11a. Three steel wire ropes were erected on the gantry, with the following diameters: φ10 mm, φ14 mm, and φ10 mm. A φ10 mm wire rope on the far right is adjustable for tightness, and was coated with grease. The leftmost φ10 mm and the middle φ14 mm wire ropes were fixed at both the top and bottom, and were not greased. The distance between the adjacent wire ropes was 200 mm. This arrangement can simulate and test the climbing performance of the robot under different working conditions of the wire rope.

The installation and disassembly process of the robot is very simple since it only requires opening the two pull buttons on the front of the robot to separate the left and right frames of the robot around the hinges, putting it on the wire rope, and then fastening the pull buttons. Finally, the clamping force between the wheels of the driven trolley and the wire rope is adjusted by the position adjustment mechanism. Thus, the robot can hover on the wire rope without slipping. The whole operation process can be completed within 1 min by a single person. The disassembly process is exactly the reverse of the previously described installation process.

To validate the performance of the robot, the project team carried out a series of experiments, such as a climbing speed test, a climbing adaptability test, a load capacity test, and an obstacle negotiation ability test.

6.1. Climbing Speed Test

In the case that no load is present, the climbing speed of the robot was calculated by measuring the time required for the robot to climb 1 m on φ14 mm grease-free wire rope several times. Through these experiments, it was found that when the output speed of the motor was 23 r/min, the robot can climb up at a speed of 40 mm/s, and move downward at a speed slightly higher (45 mm/s). Compared with the climbing speed of the first-generation climbing robot WRR-I developed in the early stages (26 mm/s) [31], the speed performance was significantly improved. However, when compared with the theoretical calculation speed of 52 mm/s the actual climbing speed of the robot was reduced, due to a certain slippage between the rubber wheel and the wire rope during the climbing process.

6.2. Climbing Adaptability Test

In order to test the climbing adaptability of the robot, it was installed on the wire ropes under five different working conditions, as shown in Figure 12. The climbing stroke was equal to 1 m up and down, and the test results are shown in Table 2.

(**a**) (**b**) (**c**)

Figure 12. The sluice wire rope under three different working conditions: (**a**) φ10 mm, without grease; (**b**) φ10 mm, with grease; (**c**) φ14 mm, without grease.

Table 2. The results of the climbing adaptability test of the robot.

	Experimental Conditions of the Wire Rope	Velocity of Upward Climbing (mm/s)	Velocity of Downward Climbing (mm/s)
1	φ10 mm, with grease, fixed at both ends	34.5	45.5
2	φ10 mm, with grease, fixed top, free bottom	32.3	47.6
3	φ10 mm, with grease, fixed at both ends, tilt angle is 60°	31.3	47.6
4	φ10 mm, without grease, fixed at both ends	38.5	45.5
5	φ14 mm, without grease, fixed at both ends	40.0	45.5

As can be seen from Table 2, the robot can stably climb on the wire rope, under various conditions. By analyzing upward climbing speeds, the robot on the non-greased wire rope was obviously faster than the one on the greased wire rope. For the same greased wire rope, the robot climbing speed was slightly faster when the two ends were fixed, when compared to the one with a single end. Regarding the angle, it is possible to conclude that the robot's climbing speed was slightly faster in the vertical case than one in the inclined case. During the downward process, the downward speed under various working conditions is generally consistent, and no obvious differences can be found. In addition, the change in the wire rope diameter has some impact on the climbing speed of the robot. As the diameter of the wire rope increased, the climbing speed increased slightly.

6.3. Load Capacity Test

In order to verify the load capacity of the robot, the robot was installed on a φ14 mm non-greased wire rope that was fixed at both ends, where loads of different weights are added on the robot, as depicted in Figure 13, with the climbing speed results shown in Figure 14. Looking at the results, it is clear that as the load increases, the upward speed of the robot slows down. When the load exceeds 10 kg, the motor is overloaded and does not move during the upward process of the robot. Regarding the downward process, the speed of the robot was relatively stable, independently of the load's weight.

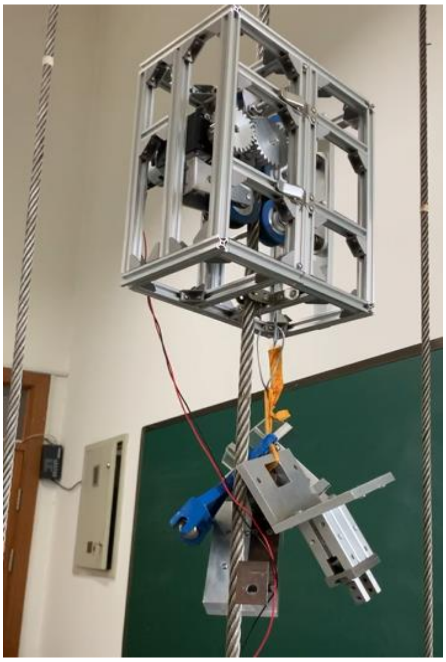


Figure 13. Load capacity test setup.

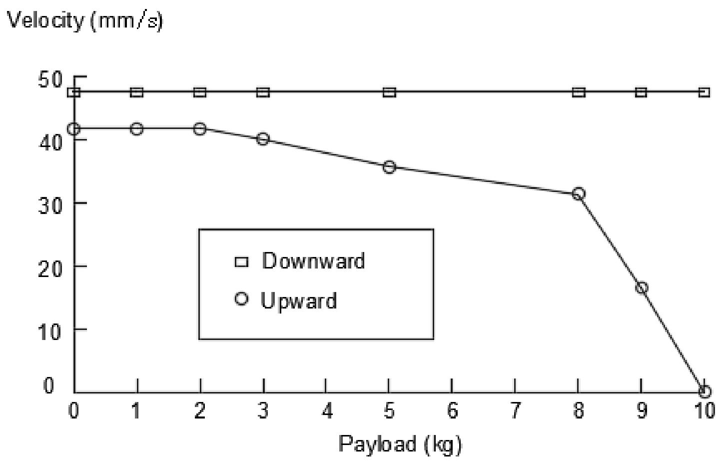


Figure 14. The results of climbing speed.

The climbing speed of the robot varies for different wire rope inclination angles and different load weights, and its relationship is depicted in Figure 15. The robot was installed on a φ10 mm non-greased wire rope that was fixed at both ends, where loads of different weights ranging from 0 to 5 kg were added onto the robot. The range of the wire rope inclination angles was from 50° to 90°. As shown in Figure 15, the climbing speed of the robot decreased significantly with the increase in load weights. For the same load, with the decrease of the inclination angle, the climbing speed of the robot decreases first and then grows.

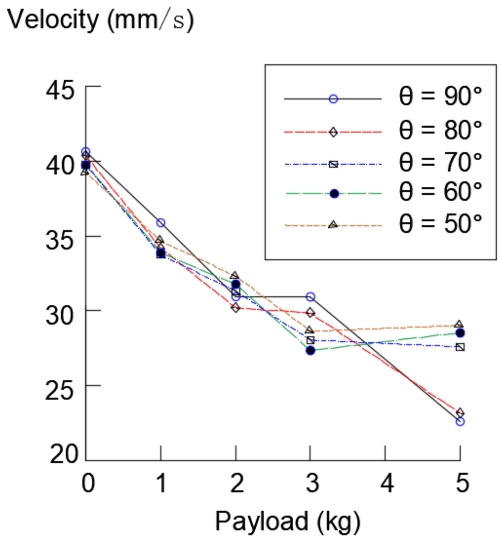


Figure 15. Depiction of the results of the climbing speed.

6.4. Obstacle Negotiation Ability Test

In order to test the robot's ability to cross obstacles, the φ14 mm wire rope was wrapped with tape to form three steps of different diameters, as shown in Figure 16. The diameters of the three steps were φ15 mm, φ16 mm, and φ17 mm, with their spacing equal to 30 mm. During the ascending process (as shown in Figure 17), the robot successfully passed three steps of different diameters but during the descending process, the robot briefly slipped at the φ17 mm step, barely passing at the end. This also reflects that wheeled climbing robots have certain deficiencies when trying to overcome obstacles.

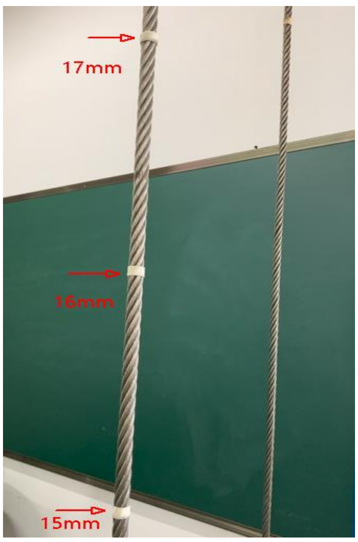


Figure 16. Obstacle negotiation ability test setup.

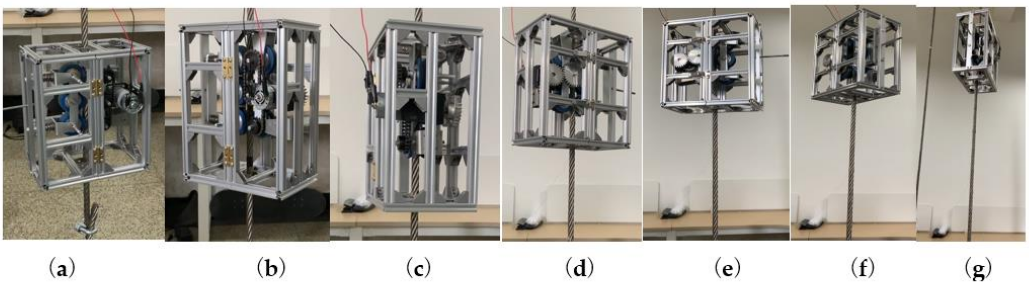


Figure 17. Process of obstacle negotiation. (**a**) t = 0 s, (**b**) t = 5 s, (**c**) t = 10 s, (**d**) t = 15 s, (**e**) t = 20 s, (**f**) t = 25 s, (**g**) t = 30 s.

6.5. Performance Comparison of the Robots

Table 3 lists some performance parameters of various rope-climbing robots. Compared with these climbing robots (WRR-I, WRC^{2}IN-I, WRC^{2}IN-II, as presented in Table 3), WRR-II is more competent for climbing small diameter wire ropes, and has better climbing performance.

Table 3. The performance comparison of the robots.

	WRR-I [31]	**WRR-II**	**WRC^{2}IN-I [5]**	**WRC^{2}IN-II [28]**
Locomotion method	Inchworm-style	Wheeled-style	Wheeled-style	Crawler-style
Attachment method	Clamp	Clamp	Clamp	Clamp
Dimensions	220 × 110 × 80 mm	250 × 150 × 300 mm	φ593 × 563 mm	328 × 507 × 701 mm
Mass	1.5 kg	3.8 kg	30 kg	26.2 kg
Payload	3 kg	8 kg	9 kg	34 kg
Diameter	10–16 mm	10–30 mm	50–90 mm	40–90 mm
Obstacle height	5 mm	3 mm	9 mm	5 mm
Climbing speed	20–26 mm/s	40–45 mm/s	35–80 mm/s	60–80 mm/s

7. Conclusions and Future Work

Both cleaning and maintenance of wire ropes have always been a major problem in the industry since there are problems regarding high labor intensity and high safety risks. The wire rope used for sluices has a small diameter and a narrow operating range, it is installed almost vertically, and is covered with grease of different degrees of hardening, which bring about greater cleaning and maintenance difficulty. Compared with the first-generation pneumatic peristaltic wire rope climbing robot WRR-I, this work proposed and described a new system, a six-wheel wire rope climbing robot (WRR-II). Under the condition of its own weight of 3.8 kg, the robot can carry a maximum of 8 kg of working tools for online laser cleaning and maintenance of steel wire ropes and visual safety inspection, thus it has a good application prospect.

The six-wheeled wire rope climbing robot proposed in this work, not only has a simple structure, a simple control, and a stable climbing speed, but it also has a large contact area and little influence on the wheel deformation of the crawler climbing robot. It was shown that it can adapt to climbing tasks of wire ropes with different diameters and different lubrication states. The theoretical analysis of the statics and kinematics of the robot, as well as the performance test of the prototype, verify the rationality and feasibility of the designed scheme. During the experiments performed with the prototype, it was also found that the V-shaped rubber wheel would have a certain slip when climbing on the surface of the wire rope covered with grease.

In future work, the project team will further optimize the structure of the rubber wheel and increase the claw-thorn structure. Therefore, it can be well adapted to the task of climbing wire rope with grease, as well as to improve the load capacity of the robot.

Some new methods that have the potential to make soft and slight robots are considered to be used to improve the robot's climbing performance, such as a fluidic rolling robot using voltage-driven oscillating liquid [32], and an active sorting of droplets by using an electro-conjugate fluid micropump [33]. What is more, it is necessary to select actual rural river sluices and coastal river sluices for outdoor field experiments, to further verify the climbing ability of the designed robot. In addition, the influence of laser cleaning devices and non-destructive testing devices on the climbing performance of the robot will also be studied, as well as the impact of wire rope maintenance.

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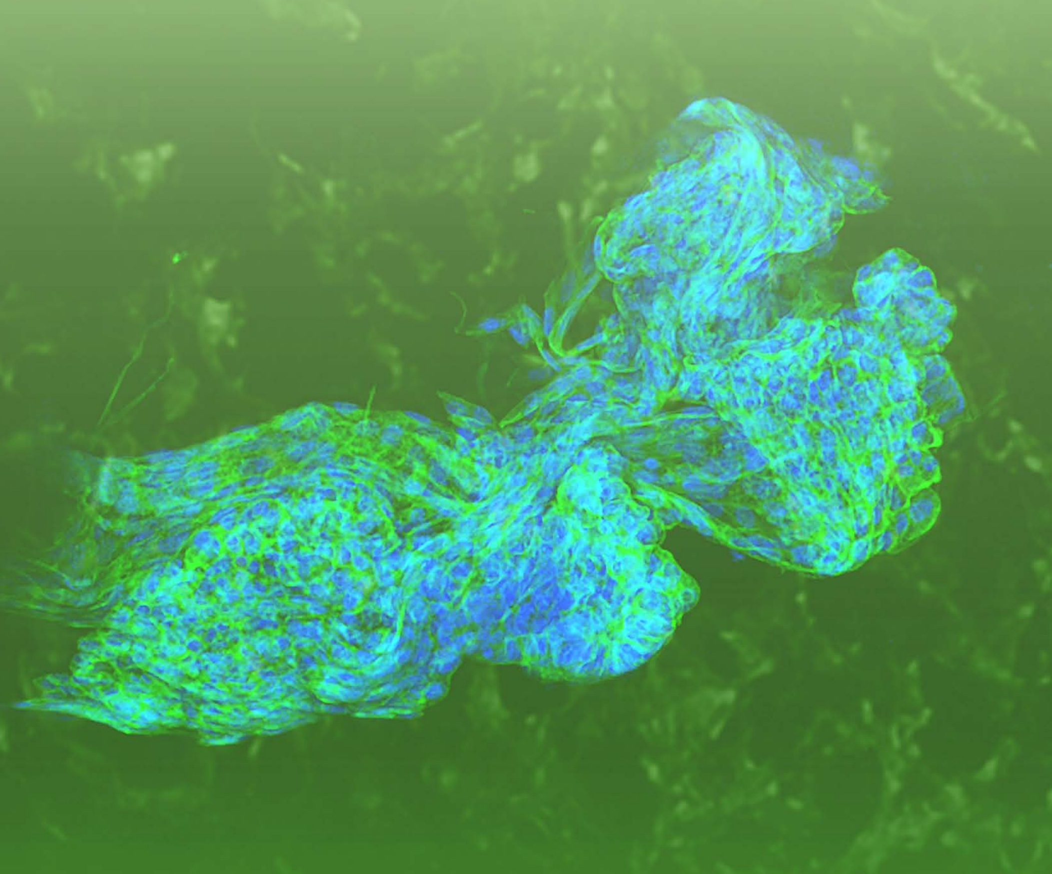

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Review

Advances in Climbing Robots for Vertical Structures in the Past Decade: A Review

Guisheng Fang and Jinfeng Cheng

Special Issue
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Review

Advances in Climbing Robots for Vertical Structures in the Past Decade: A Review

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Abstract: Climbing robots are designed to conduct tasks that may be dangerous for humans working at height. In addition to improving safety, they can also increase task efficiency and reduce labor costs. They are widely used for bridge inspection, high-rise building cleaning, fruit picking, high-altitude rescue, and military reconnaissance. In addition to climbing, these robots need to carry tools to complete their tasks. Hence, their design and development are more challenging than those of most other robots. This paper analyzes and compares the past decade's design and development of climbing robots that can ascend vertical structures such as rods, cables, walls, and trees. Firstly, the main research fields and basic design requirements of climbing robots are introduced, and then the advantages and disadvantages of six key technologies are summarized, namely, conceptual design, adhesion methods, locomotion modes, safety mechanisms, control methods, and operational tools. Finally, the remaining challenges in research on climbing robots are briefly discussed and future research directions are highlighted. This paper provides a scientific reference for researchers engaged in the study of climbing robots.

Keywords: vertical structure; climbing robot; application fields; adhesion mechanism; locomotion mode; control mode; operation tools

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1. Introduction

Climbing robots can replace human workers in tasks where they are required to climb along vertical or near-vertical objects. They can carry tools to conduct a wide range of hazardous tasks, such as detection, monitoring, cleaning, maintenance, installation, spraying, fruit picking, pruning, search and rescue, and so on. They are widely used in bridges, ships, chimneys, pipelines, streetlamps, nuclear power plants, wind power generation, high-rise buildings, agricultural picking, and other fields.

Since the first climbing robot, Mod-I, was developed by Nishi et al. [1] in the 1960s, climbing robots have attracted the attention of many research institutions and scholars. A large number of scientific research achievements and robot prototypes have emerged. In the past decades, scholars from all over the world have summarized the climbing robots made for use in different fields. Yun et al. [2] discussed the development status of bridge-cable-climbing detection robots. Megalingam et al. [3] summarized the technologies related to coconut-tree-climbing robots. Solanki et al. [4] elaborated on two key technologies of wall-climbing robots—the attachment method and motion mechanism. Fang et al. [5] reviewed the research progress of three different motion modes of wall-climbing robots: wheeled, crawler, and legged. In addition, they summarized four different adsorption technologies used in wall-climbing robots: negative-pressure adsorption, magnetic adsorption, bionic adsorption, and electrostatic adsorption. Seo et al. [6] summarized the climbing mechanisms, cleaning methods, and applications of robots used to clean the glass and facades of high-rise buildings. Cai et al. [7] and Hou et al. [8] discussed the research status of robots used for high-rise buildings and for defect detection on bridge cable surfaces, respectively. Bogue et al. [9] discussed the research status and potential applications of climbing robots. The above papers discussed the research status of climbing robots from the perspective of one or several application fields or key technologies. This paper focuses on a discussion of the six key technologies of climbing robots used for various vertical structures: their conceptual design, adhesion mechanisms, locomotion modes, safe-landing methods, control modes, and operation modes.

2. Overview of Research on Climbing Robots Used for Vertical Structures

The main types of climbing robots used for vertical structures are pole-climbing robots, pipe-climbing robots, tree-climbing robots, wall-climbing robots, cable-climbing robots, and robots that climb other irregular objects.

2.1. Pole Climbing Robot

Poles or tubes are widely used in streetlamps, lightning rod poles, building pipelines, and other structures. Most of these are cylindrical structures with diameters of 10–500 mm and lengths of a few meters to tens of meters. Some are variable-diameter structures, being wider at the bottom than at the top. The overall surfaces of the poles or tubes are smooth, some of which have steps and bending states. Pole-climbing robots are mainly used for surface detection, cleaning, and spraying of poles or tubes, as well as the maintenance of objects on poles.

With respect to pipe-climbing robots, Guan et al. [10,11] developed a truss-climbing robot called Climbot. The robot is composed of five single-degree-of-freedom joints and two claws and can climb truss structures and change lightbulbs. Noohi et al. [12] designed a pole-climbing robot called UT-PCR for the cleaning and maintenance of highway lamps. The robot consists of a triangular trunk and six mechanical arms with rubber wheels. In the climbing process, the robot can not only correct its deviations automatically but also cross a certain height of steps. Han et al. [13] designed a climbing robot for the nondestructive testing (NDT) of large pipe structures. The robot is composed of two driving modules and a driving connecting arm, and can cross external obstacles such as fixtures, flanges, and valves, as well as pipe components such as elbows and T-branch joints. Unlike robots that climb pipes from the outside, Agarwal et al. [14] designed a robot that can climb vertically within a pipe. The robot is composed of three symmetrically arranged track modules, which have two-way movement and can pass through internal complex T-shaped pipes and elbow networks at different angles. Verma et al. [15] developed a pneumatic-driven pipe-climbing soft robot. The robot is composed of a buckling pneumatic actuator and two pressure-drive rings. It can maintain climbing and cleaning performance even in wet conditions and underwater.

This review indicates that most pole-climbing robots are still in the stage of laboratory research and can only climb straight rods or tubes. Some robots can climb elbows and have a certain ability to negotiate obstacles and adapt to variable pipe diameters. A few robots have simple operation abilities and certain practical value. The adhesion of these robots is mostly achieved by clamping, while their locomotion is mostly of the inchworm type or wheeled type.

2.2. Tree-Climbing Robots

Trees are very different from rods and tubes as they have bark and branches, irregular shapes, and mostly uneven surfaces. In addition, their diameters can vary greatly, ranging from a few centimeters to more than ten meters. Tree-climbing robots can replace human workers in dangerous tasks such as pruning branches, picking fruit, pest elimination, and biological observation.

Lam et al. [16–20] developed a flexible tree-climbing robot, dubbed Treebot. It adopts innovative omnidirectional tree grippers and a continuum maneuver structure, and thus can adapt to a variety of tree species and achieve free switching from trunks to branches. It can be used to help workers with tree cultivation and biological observation. Ishigure et al. [21]

developed the tree-pruning robot. It is composed of an up–down climbing mechanism, a steering mechanism, a posture adjustment mechanism, a chain saw mechanism, and a controller. Relying on self-weight and an energy-saving chainsaw drive, the robot can climb trees and prune them with low power consumption. Diller et al. [22] developed a tree-climbing robot named DIGbot, which can climb tree trunks. The robot consists of a body and six legs. Using a hook and claw installed on the legs, the robot can climb in all directions on rough trunks and can perform turns. Wibowo et al. [23] developed a coconut-harvesting robot, which adopts the spring-clamping and wheel-climbing methods. It can climb coconut trees with different diameters and carry cameras and blades to detect and cut down coconuts. Fu et al. [24] developed a robot for the pruning of fast-growing forests, which is composed of a wheel-climbing mechanism, a spring-clamping mechanism, and a ring-pruning mechanism. It weighs about 40 kg and can climb trunks with diameters of 150–350 mm at a speed of 20 mm/s, and can cut branches with a maximum diameter of 30 mm. Wright et al. [25] developed a multi-module snake-like tree-climbing robot dubbed Uncle Sam. The robot uses the spiral method to achieve the climbing movement, with a body that is wound around the trunk in a spiral. Upward and downward climbing movement is realized through synchronous rolling of the body.

This review of tree-climbing robots indicates that most robots can only climb straight trunks, while a few can transfer between trunks and branches and carry tools. Their adhesion modes are mostly clamping or claw stabbing, and their locomotion modes are mostly by wheels or tracks.

2.3. Cable-Climbing Robots

Cables and wire ropes are widely used in bridges, ships, cableways, hoisting machinery, and other scenarios. To ensure normal equipment operation, these cables need regular inspection, maintenance, and repair. The difference between a cable and a wire rope is that the periphery of a wire rope generally has no protective layers, while most cables do. A wire rope without a protective layer has a spiral shape and a certain flexibility. In contrast, a cable with a protective layer is cylindrical and more similar to a rod or tube. However, the protective layer is relatively soft compared with a rod or tube, and so it can be easily damaged while the robot is climbing. In addition, for suspension bridges or cable-stayed bridges, the cables are generally tens of meters or even hundreds of meters long, and some protective layers have cracks or bulges.

Ding et al. developed four generations of cable-climbing robots: CCRobot-I [26], CCRobot-II [27], CCRobot-III [28], and CCRobot-IV [29,30], as shown in Figure 1a–d. CCRobot-I is composed of a clamping module and a parallel manipulator. It weighs about 15 kg, has a load capacity of more than 30 kg, and its maximum climbing speed can reach >3 m/min. CCRobot-II adopts a palm-based grasping module and an alternate sliding frame mechanism, so its climbing speed can reach 5.2 m/min. It has a mass of 25 kg and maximum payload of 30 kg. To further improve climbing speed and payload capacity, CCRobot-III adopts a split-wire-driven method, being composed of a climbing precursor and a main frame. These two parts are connected and driven by steel wires. The climbing precursor acts as a moving anchor and moves quickly on the bridge cable. The main frame acts as a mobile winch, carrying the payload and pulling itself to a specific position with steel wires. It can climb at a speed of 12 m/min and can carry a load of more than 40 kg. The structure of CCRobot-IV is similar to that of CCRobot-III; it also consists of a climbing precursor and a payload-carrying body. The difference is that the new climbing precursor is replaced by a quad-ducted propeller-driven climbing system. CCRobot-IV can maintain a climbing speed and an optimal turning behavior of 12 m/min with a 40 kg payload. Its maximum climbing speed can reach 20 m/min. Wang et al. [31] designed the wheeled cable-climbing robot shown in Figure 1e. The robot is connected by two separate car modules through four turnbuckles to form a closed structure. The robot has a self-weight of 12 kg, can carry a maximum load of 8 kg, and can overcome obstacles 2.42 mm high. Xu and Wang et al. [32–36] designed a series of cable-climbing robots. The first generation of the wheeled cable-climbing robot, Model-I, is shown in Figure 1f. It is composed of three equidistant circular modules, which are connected by six connecting plates to form a closed hexagonal body for clamping cables. Each module includes two wheels for climbing, a CCD camera for visual inspection, two pairs of driving permanent magnets, and five Hall sensors for detecting magnetic leakage. It can perform defect-detection tasks on cable-stayed bridge cables. Subsequently, the project team designed an improved Model-II robot composed of two equally spaced modules connected by rods to form a closed hexagonal body that is fixed on the cable (Figure 1g). With the aim of building a robot able to detect broken wires within a spiral cable, the project team developed the Model-III robot in 2014 (Figure 1h), which is composed of a driving car and upper and lower support rods. The driving trolley and supporting connecting rods are connected through a fixed joint and installed relative to each other along the cable. A climbing device is installed on the body of the robot, which allows the car to rotate freely to adapt to guidelines with different pitches on the cables. In 2019, Xu et al. made further improvements by increasing the flexibility of the wheels via an extension spring and swingarm to achieve an obstacle-climbing function (Figure 1i). In view of the difficulties in detecting and repairing damaged bridge cables, Xu et al. designed the Model-IV cable-climbing robot based on independent quadrilateral suspension in 2021 (Figure 1j). The robot can automatically repair damaged bridge cables using testing, grinding, cleaning, spraying, and winding devices.

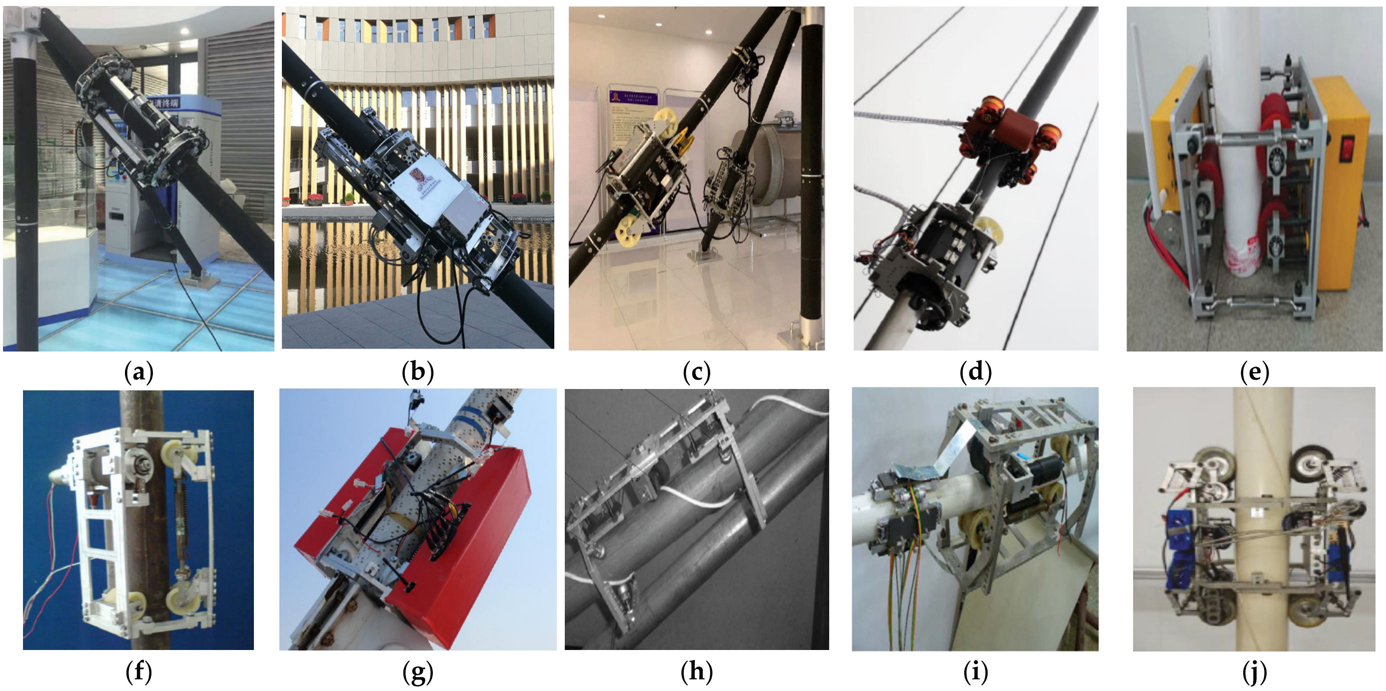
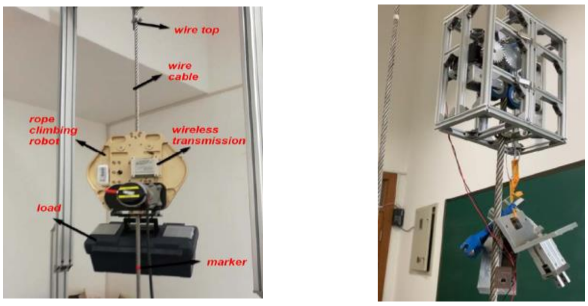


Figure 1. Cable-climbing robots. (**a**) CCRobot-I [Reproduced from [26] with permission from Ning Ding]; (**b**) CCRobot-II [Reproduced from [27] with permission from Ning Ding]; (**c**) CCRobot-III [Reproduced from [28] with permission from Ning Ding]; (**d**) CCRobot-IV [Reproduced from [29] with permission from Ning Ding]; (**e**) Robot [Reproduced from [31] with permission from Ning Ding Bin He]; (**f**) Model-I [Reproduced from [32] with permission from Fengyu Xu]; (**g**) Model-II [Reproduced from [33] with permission from Fengyu Xu]; (**h**) Model-III [Reproduced from [34] with permission from Fengyu Xu]; (**i**) Robot [Reproduced from [35] with permission from Fengyu Xu]; (**j**) Model-IV [Reproduced from [36] with permission from Fengyu Xu].

Cho et al. [37–40] designed three wire-rope-climbing and detection robots, named WRC^2IN-I, WRC^2IN-I+, and WRC^2IN-II. WRC^2IN-I is composed of a wheel-drive mechanism, an attachment mechanism, and a safe-landing mechanism. It can climb at 0.05 m/s with a 15 kg load. When a wheeled cable-climbing robot moves on an uneven cable surface, it produces periodic vibrations that affect detection accuracy. Therefore, the project team improved the first-generation robot by changing its wheeled structure into a tracked structure, which greatly reduces the vibration problem. To further simplify the installation and disassembly processes of the first-generation robot and improve its work efficiency, the project team developed the second-generation cable-climbing robot WRC^{2}IN-II. The robot is composed of two separable attachment modules, two driving modules, and two obstacle-surmounting sub-modules. The improved robot can carry a load of 24 kg, while its installation and disassembly time is only about 5 min. Sun et al. [41] designed a wire-rope-climbing robot for detecting lamps at the top of streetlights at airports (Figure 2a). It is composed of a compression mechanism, a suspension mechanism, and a tracked movement mechanism. Its weight is 16 kg, and it can carry a 58 kg load. Ratanghayra et al. [42] designed a simple rope-climbing robot composed of a mounting frame and four mutually staggered wheels with motors. The wheels are pressed onto the rope by springs and can adapt to ropes of different diameters. Fang et al. [43] designed a six-wheeled wire rope-climbing robot called WRR-II for the maintenance of sluice wire ropes (Figure 2b). The developed climbing robot is composed of separable driving and driven trolleys. It adopts the spring clamping mechanism and the wheeled movement method. It can carry a camera and a laser-cleaning device to detect and clean sluice wire ropes.



(**a**) (**b**)

Figure 2. Rope-climbing robots. (**a**) Robot [Reproduced from [41] with permission from Guanglin Sun]; (**b**) WRR-II [Reproduced from [43] with permission from Guisheng Fang].

This review of cable-climbing robots indicates that most research focuses on cable safety detection in cable-stayed bridges. A few are used for climbing wire ropes and soft ropes. The attachment modes are mostly clamping-type, while their movement modes are mostly wheeled-type and tracked-type.

2.4. Wall-Climbing Robots

Wall-climbing robots are widely used in the construction, shipbuilding, chemical, military, fire protection, and service industries, among others. They have become a focus of research on climbing robots, and hundreds of prototype systems have emerged so far. Compared with rods, trees, and other objects, walls have a large area. Walls can be rough or smooth, and some also have grooves and bulges, which creates challenges in the design of wall-climbing robots.

Heredia et al. [44] designed a window-cleaning robot named Mantis. It adopts three connected vacuum cup adsorption modules and a crawler movement mode. It uses translational and steering movement, while also independently crossing panes for glass cleaning. Bisht et al. [45] designed a robot for cleaning exterior glass walls that adopts the crawler movement mode and vacuum adsorption mode. It can carry a roller brush to clean glass curtain walls. Xiao et al. [46] designed a wall-climbing robot called the Rise-Rover, which has high reliability and strong load-bearing capacity. The robot adopts the pneumatic adsorption method and crawler-climbing method, and can quickly climb vertical walls with small grooves. Eto et al. [47] developed the WCR-Eto wall-climbing robot for hull welding, which uses a pair of two free rocker-arm hovering mechanisms with magnetic ball wheels to adapt to surfaces with a variety of shapes. It can cross 90° corners and 50 mm high obstacles. Milella et al. [48] and Eich et al. [49] developed crawler and wheeled climbing robots, respectively, for hull inspection tasks. Both robots use permanent magnets for adsorption and can perform real-time detection of hull defects with autonomous navigation. Seoul National University, South Korea, together with the Lingnan and Carnegie Mellon Universities, USA, developed four multi-connected crawler wall-climbing robots named MultiTank, FCR, Combot, and MultiTrack [50]. They use flat dry rubbers, rubber magnets, or suction cups as attachment devices, and all adopt the crawler drive mode. They can climb with a load in indoor, heavy industry, and building exterior wall scenarios, and have the ability to climb obstacles from plane to plane and from plane to circular arc. Souto et al. [51] developed a sandblasting robot for unsupervised automatic cleaning of large ships (Figure 3a), which adopts a separable double-frame structure to achieve alternating translation and rotation. Alkala et al. [52] designed a climbing robot named EJBot for the needs of petrochemical container detection (Figure 3b). It is composed of a propeller-drive unit, a wheel-drive unit, and a wireless control unit. It can adapt to climbing and detection tasks on a variety of surfaces with different materials and bending degrees and can cross 40 mm high obstacles. Lee et al. [53] designed a modular wall-climbing cleaning robot that can surmount obstacles for the cleaning of exterior glass walls of buildings. The robot is composed of a main platform and three independently scalable modular climbing units. The robot uses a winch at the top of a building to move up and down and uses an air pressure adsorption device and cleaning device in its middle module to bring the robot close to the wall for cleaning tasks. Each module is equipped with sensors to detect obstacles and walls so that the robot can automatically avoid obstacles.

(**a**) (**b**)

Figure 3. Wall-climbing robots.; (**a**) sandblasting robot [Reproduced from [51] with permission from Richard J. Duro]; (**b**) EJBot [Reproduced from [52] with permission from Mohamed Gouda Alkalla].

This review of wall-climbing robots indicates that most current research focuses on tasks related to buildings and hulls. The attachment modes are mostly vacuum or magnetic adhesion, and the moving modes are mostly tracked-type or wheeled-type.

2.5. Climbing Robots for Other Irregular Vertical Structures

In addition to pole-, tree-, and wall-climbing robots, climbing robots have been designed for performing detection and maintenance tasks on irregularly shaped vertical structures. For example, there are robots for steel bridge climbing, tower climbing, wind turbine blade climbing, and cloth climbing.

Among steel bridge detection robots, Nguyen and La et al. [54–60] designed the crawler and hybrid climbing robots. The crawler-climbing robot uses a reciprocating mechanism and a roller chain, which enables it to climb on structures with different shapes and from one surface to another. The hybrid climbing robot uses a combination of wheels and legs for climbing. On the smooth surfaces of a steel bridge, it can use the wheels to move quickly. When it needs to cross obstacles or realize plane conversion, it can use its legs. Pagano et al. [61] designed a seven-degree-of-freedom (7-DOF) inchworm-like climbing robot, and adopted a real-time path planning method based on the LOS algorithm so that the robot can climb autonomously in restricted areas within steel bridges. Wang et al. [62] designed a four-wheel climbing robot composed of a body, four magnetic wheels, a steering system, and a shock absorber. The robot can climb vertical surfaces and reverse horizontal surfaces and can cross complex obstacles, such as bolts, steps, convex corners, and concave corners. Ward et al. [63] designed an inchworm-like climbing robot called CROC, which consists of a seven-DOF trunk and two magnetic foot pads. Each magnetic foot pad includes three independently controlled magnetic toes. The robot can perform 360° plane conversion and pass through manholes.

For the inspection and maintenance of transmission towers, Lu et al. developed two climbing robots dubbed Pylon-Climber I [64] and Pylon-Climber II [65]. Both robots use gripper adhesion and step-by-step driving. They can climb straight angle irons, cross between angle irons, and climb over obstacles such as bolts. Compared with Pylon-Climber I, Pylon-Climber II has improvements in its clamping jaw design. Instead of clamping the entire angle iron, it only clamps a single side, making its structure simpler and more efficient. Yao et al. [66] designed a series-parallel hybrid transmission-tower-climbing robot composed of two parallel legs with 3-DOF delta mechanisms and a trunk linkage mechanism. The legs are equipped with electromagnets, which can be adsorbed onto the transmission tower. Relying on inchworm gait control, it can achieve climbing and obstacle negotiation functions.

Lee et al. [67] designed a climbing robot for the maintenance of offshore wind turbines. It has a rectangular frame structure composed of four risers, two grippers, two operating arms, and a mobile scissor device. The robot can climb towers or blades and performs cleaning and inspection using waterjets and phased array ultrasonic testing (PAUT) devices, respectively. Birkmeyer et al. [68] developed a robot called CLASH that can climb loose vertical cloth. Liu et al. [69] also developed a soft-cloth-climbing robot named Clothbot. It uses two wheel-shaped clamping claws to clamp onto the wrinkles of clothes, and uses a 2-DOF omnidirectional tail to adjust the center of the robot so that it can maintain its balance and change its rotation direction.

Designing robots to climb irregular objects with highly variable structures and shapes is difficult, and general adhesion mechanisms and locomotion modes remain lacking.

3. Basic Design Requirements of Climbing Robots for Vertical Structures

Climbing robots are mainly used to carry out risky tasks in hazardous environments, so they require certain basic characteristics, such as functionality, a light weight, strong load-carrying capacity, flexible movement, a fast climbing speed, high safety, strong environmental adaptability, and the ability to climb objects without damaging their surfaces, as detailed below:

(1) Functionality. This is the primary consideration in climbing robot design. Each has a purpose, such as detection, cleaning, spraying, installation, or maintenance. Therefore, in addition to a basic climbing ability, climbing robots also need to have a certain load-carrying ability, such as the ability to carry a camera or a nondestructive testing device for defect detection, cleaning equipment, or a manipulator for installation and disassembly tasks.

(2) Lightweight structure. Climbing robots should be as light as possible to minimize their size and energy consumption.

(3) Fast climbing speed. Robots are mainly used to replace skilled workers to conduct tasks that are difficult, hazardous, or boring, so their work efficiency must be higher than that of humans.

(4) Good environmental adaptability. The objects that need to be climbed are diverse and have different shapes, so climbing robots need good environmental adaptability to be able to climb objects of various diameters, lengths, materials, shapes, tilt angles, and surface roughnesses.

(5) Obstacle negotiation ability. The surfaces of climbed objects are not always flat and smooth. Some have bulges, pits, steps, or forks, which requires robots to have good obstacle negotiation abilities.

(6) Working safely and reliably. During the climbing process, a robot can experience a power failure, jammed mechanism, or other fault. Working at heights can cause vibrations and shaking due to wind, which can affect the safety of robots and their operators. This requires robots to have a self-protection ability so that they will not fall from height in the case of a power failure or can be safely recovered in case of jamming.

(7) A general installment interface. Climbing robots should have a general installment interface and carry multiple tools that can be changed as the robot is working to expand its functional range. In addition, the impact of the tools on the robot's performance should be minimized.

(8) Other factors to be considered include structural size, cost, energy supply mode, and installation and disassembly times. Some working spaces are limited, necessitating a small robot. Robots powered by a cable may be unsuitable for work on long objects. In addition, manufacturing costs must be considered; accordingly, components and modules that can be bought online should be preferred.

4. Key Technologies Used in Climbing Robots

4.1. Conceptual Design of Climbing Robots

Conceptual design is an early stage in the product design process that has an essential effect on robot innovation. The conceptual design of robot products describes the combination of principal components used in the space or structure required to meet the customers' functional requirements. Once the conceptual design is completed, 60–70% of the product design is determined. Therefore, conceptual design is very important and is key to distinguishing between products.

For climbing, most robots adopt a conceptual design with conventional structural shapes, such as rectangular structures, triangular structures, hexagonal structures, and circular structures. For example, the tree-climbing robot designed by Gui et al. [70] adopts a triangular structure, being composed of three symmetrically distributed wheel mechanisms. The cable-climbing robot designed by Xu et al. [33] adopts a rectangular structure, which is connected by two symmetrical modular trolleys.

Many animals have good climbing abilities, such as geckos, cockroaches, spiders, inchworms, sloths, monkeys, snakes, cats, and beetles. Inspired by animals, researchers have designed various bionic climbing robots. Wang et al. [71] designed a quadrupedal tree-climbing robot that mimics the tree-climbing movements and postures of monkeys. Liu et al. [72] designed a climbing robot that adopts a five-link mechanism and a piston mechanism to imitate the climbing movement of geckos. Bian et al. [73] designed a foldable climbing robot that imitates the attachment and climbing mechanisms of longicorns and geckos, as shown in Figure 4a. By imitating the attachment mechanism of cicadas and geckos and the gecko climbing gait, Bian et al. [74] designed a gear-and-link-driven climbing robot, as shown in Figure 4b. Kanada et al. [75] imitated the operating mechanism of leeches and designed a soft climbing robot called LEeCH. Yanagida et al. [76] designed a climbing robot named Scorpio, which imitates the crab spider species Cebrennus rechenbergi. Inspired by the behavior of arboreal snakes in climbing tree trunks, Liao et al. [77] designed a snake-like winding-pole-climbing soft robot. Han et al. [78] developed a caterpillar-inspired segmented robot that can climb vertical surfaces.

(a) (b)

Figure 4. Bionic climbing robots. (**a**) longicorn-like robot [Reproduced from [73] with permission from Deyi Kong]; (**b**) cicada- and gecko-like robot [Reproduced from [74] with permission from Deyi Kong].

In addition to climbing biomimetics, researchers have also designed climbing robots that imitate the growth and climbing actions of plants. Fiorello et al. [79] provided an overview of the methodological approaches and tools exploited by researchers for extracting the relevant biological features of climbing plants that might be adapted to design the plant-inspired robotics under three main themes: adapation, movements, and behavior. Mazzolai et al. [80] offered a brief review of the fundamental aspects related to a bioengineering approach in plant-inspired robotics, including the movement mechanism of roots and the attachment and climbing mechanisms of shoots.

4.2. Adhesion Methods

Climbing robots often need to adhere to different vertical surfaces. Commonly used adhesion methods include magnetic adsorption, air pressure adsorption, clamping adhesion, claw grasping, electrostatic adsorption, and biological adhesion.

4.2.1. Magnetic Adsorption

The magnetic adsorption method adopts a permanent magnet or electromagnet (or a combination) and is suitable for use with ferromagnetic objects.

Permanent magnet adsorption is one of the most common magnetic adsorption methods. It can be divided into contact and non-contact types according to whether the magnet is in contact with the surface of the climbed object. Contact permanent magnet adsorption involves a combination of a permanent magnet and a moving mechanism. For instance, Erbil et al. [81] adopted the magnetic wheel method in the PC-101 pole-climbing robot. Fourteen magnets are arranged on each wheel in the circumferential direction. As the wheel rotates, two or three magnets always act on the pole. The MIRA climbing robot designed by Ahmed et al. [82] is composed of a group of permanent magnets that are regularly arranged and embedded into a polyurethane wheel frame. Tavakoli et al. [83,84] designed four generations of magnetic omnidirectional wheels in the Omnilimbers climbing robot. The first generation of magnetic wheels adopted integral ring magnets, the second generation adopted a magnet array, the third generation featured an evenly arranged magnet array in the middle of an omnidirectional wheel, and the fourth generation adopted magnetic rollers.

Contact permanent magnet adsorption systems have a compact structure but cause wear during movement. Non-contact permanent magnet adsorption systems have separate mechanisms for adsorption and movement, leaving a gap between the adsorption device and the surface. For example, Howlader et al. [85] used a non-contact permanent magnet adsorption mechanism in a reinforced-concrete wall-climbing robot. The robot is composed of a mobile platform, four wheels, and a magnetic adsorption module fixed under the mobile platform. The magnetic adsorption module is 2 mm away from the wall, with a yoke and 3 N42 neodymium magnets arranged in the N-S-N direction, which significantly increases its adsorption force. Yan et al. [86] adopted a multi-directional magnetized permanent magnet adsorption device (PMAD) with adjustable spacing in a climbing detection robot for a hydropower station. The magnetic adsorption device is composed of multiple groups of permanent magnet arrays and a magnetizable base. The robot adjusts the position of the PMAD through a connecting rod and screw pair mechanism to dynamically adjust its adsorption force. Ding et al. [87] adopted a non-contact permanent magnet adsorption device with surface adaptability in a wall-climbing robot developed for ultrasonic weld detection in spherical tanks. There is a gap of 5–8 mm between the magnetic device and the surface. This scheme not only achieves higher magnetic energy utilization than magnetic tracks or magnetic wheels but also has the flexibility of magnetic wheel technology. To ensure a stable adsorption force for robots climbing irregular or large-radius surfaces, Silva et al. [88] adopted an adsorption device that can dynamically adjust the position of the permanent magnet. The device uses two inductive sensors to maintain a constant distance between the magnet and the climbed surface via a worm-drive shaft to keep the adsorption force stable.

In permanent magnet adsorption, the magnetic force is fixed. While energy is not required to maintain the magnetic force, it cannot be turned off. To solve this problem, switchable permanent magnets have been used. For example, Tavakoli et al. [89] used switchable MagJig 95 magnets in the Omnilumber-II climbing robot. Using a handle connected to the top of the robot, the user can manually rotate the moving magnet to switch it on and off. However, this device can only switch the magnetic force on or off and cannot adjust its strength.

Electromagnetic adsorption uses the electromagnetic principle to energize an internal coil to generate a magnetic force. Electromagnetic adsorption has also been used in climbing robots because it can be used to switch the magnetic force on and off as well as adjust its strength. For example, Minibobot [90] uses two electromagnetic feet with an alternating adsorption action for climbing. Han et al. [91] designed a distributed electromagnetic adsorption device in a hull-rust-removal robot. The robot uses a double-chain crawler as the mobile device, with an electromagnetic adsorption device installed on a track, allowing it to move with the crawler. According to the electromagnetic adsorption principle and control requirements, a distributed control mode is used to accurately adjust the magnetic force of each part of the adsorption module.

In addition to permanent magnetic adsorption and electromagnetic adsorption, hybrid magnetic adsorption devices based on their advantages have been designed. For example, Cardenas et al. [92] designed a magnetic wheel that uses electro-permanent-magnet (EPM) adsorption technology. The magnetic wheel is composed of two permanent magnets with different magnetism (such as neodymium and Alnico5), two magnetic poles, and copper-enameled coils. EPM allows the magnetic force to be controlled by simply applying a short electrical pulse to the coil winding. By controlling the amplitude of the electric pulse, the magnetic force can be adjusted to the required value to realize continuous changes in magnetic adhesion.

The main advantage of magnetic adsorption methods is that their adsorption force is strong. Permanent magnets do not need additional energy, or only a small amount. Electromagnets can control the magnetism by switching on and off. The disadvantage of magnetic adsorption is that it is not applicable to non-ferromagnetic materials such as cement, brick, or stainless steel. Furthermore, some applications need to be electromagnetic-proof and explosion-proof. The magnetic adsorption force is related to the area of the magnet and the distance between the magnet and the metal surface. Its strength decays rapidly with distance from the object's surface. Magnets are generally heavy, which increases the weight of the robot and reduces its load-carrying capacity. For permanent magnets, the magnetic force is fixed and difficult to eliminate. Electromagnets need an uninterrupted power supply. When power is lost, the magnetic force will disappear, posing certain safety risks.

4.2.2. Air Pressure Adsorption

On large and flat surfaces, climbing robots often use air pressure adsorption, which may be active or passive. Active adsorption uses a vacuum, negative pressure, or aerodynamic adsorption. Passive adsorption uses suction cups without additional vacuum pumps or negative-pressure chambers.

Vacuum suction is the most common air pressure adsorption method. It exhausts the air from a suction cup using a vacuum pump to adhere to the climbed surface. Guan et al. [93] used a vacuum adsorption device in a bipedal wall-climbing robot called W-Climbot. The adsorption device consists of three suction cups, a support plate, a dry rotary vacuum pump, and some accessories. Three cups are mounted on the vertices of the equilateral triangle of the support plate, which can reduce the tilt of the robot caused by the deformation of the suction cups. Pressure sensors are installed in the suction cups to measure the vacuum inside the cup and output it to a low-level controller in real time to achieve closed-loop pressure control and a stable adsorption force. Vacuum adsorption is easy to control and has a high load capacity. It is not limited by the surface material but by its quality and is generally suitable for smooth planar objects. The strength of its adsorption force is related to the pressure difference and adsorption area. If there are holes or gaps in the surface, the adsorption force will be greatly reduced. In addition, vacuum adsorption requires a vacuum pump and a good sealing chamber, which increase the energy consumption, weight, and noise level of the robot.

Negative-pressure adsorption uses the adsorption force generated by an impeller or eddy current to fix the robot to a surface. An eddy current can cause local negative pressure via a rapidly spirally rotating airflow in a closed cavity, which is somewhat similar to the tornado effect. For example, Zhao et al. [94] adopted the eddy current adsorption method in the Vortexbot wall-climbing robot. The adsorption mechanism consists of a vortex ring, an annular skirt, an upper cover, and four symmetrically distributed nozzles. Airflow through the four nozzles creates negative pressure in the vortex chamber, which presses the robot against the surface. Eddy current adsorption does not require suction cups, so it can adapt to rough surfaces and obstacles. The negative-pressure adsorption method was adopted in the LARVA wall-climbing robot developed by Koo et al. [95]. The adsorption mechanism consists of a vacuum chamber, an impeller with a motor, and a double-layer sealing device. When the motor drives the impeller, the air in the vacuum chamber is expelled, creating a pressure difference between the environment and the vacuum chamber, so that the robot adheres to the surface. Parween et al. [96] used two negative-pressure adsorption modules in the Ibex climbing robot. Each adsorption module consists of a main suction chamber, suction cups, impellers, and connectors. Through rotation of the impeller, a pressure difference is generated between the main suction chamber cavity and the atmospheric pressure. The suction cup is equipped with a skirt that maintains the pressure differential in the chamber and creates a positive force that keeps the suction cup attached to the surface.

Aerodynamic adsorption uses the wind generated by a propeller to attach a robot to a surface, allowing it to adapt to surfaces of various shapes. Faisal et al. [97] developed a wall-climbing robot that uses the air pressure difference thrust generated by two ducted fans to attach the robot to a wall. Sukvichai et al. [98] used a double-propeller attachment mechanism in a wall-climbing robot. The two propellers have the same structures with opposite directions of rotation and can be controlled by servo motors for angle adjustment, so that the robot can achieve two-wheel attachment and four-wheel attachment according to the climbing conditions. Mahmood et al. [99] adopted a propeller-type attachment mechanism in the UOTWCR-II wall-climbing robot. It consists of two left-hand and right-hand rotor systems and two drive wheels. Another front steering wheel is connected to the structure to support the robot. The left rotor has a clockwise thruster, while the right rotor has a counterclockwise thruster. The two rotors rotate in different directions, creating a downward thrust that keeps the robot attached to a surface.

Passive adsorption uses multiple suction cups to alternately engage and disengage, so that the robot can attach to a flat surface. Passive adsorption systems are lightweight and quiet because they do not require a vacuum pump or negative-pressure device. They have been used in the design of plane-climbing robots. For example, Ge et al. [100,101] used a passive suction cup structure in a smooth-wall-climbing robot. Multiple passive suction cups are fixed on the outer surface of the crawler at equal intervals and rotate with the crawler. Under the action of a guide rail, they can be attached to the wall and then pressed and separated.

In addition to conventional pneumatic adsorption methods, some new methods have emerged, such as vibration adsorption. Chen et al. [102] installed a vibration adsorption device on the feet of a gecko-shaped wall-climbing robot. The adsorption device consists of four parts: a vibrating mechanism, an air-releasing mechanism, a guiding mechanism, and a stability retainer. The vibration mechanism generates periodic vibrations so that the suction cup on it can generate a stable negative pressure and adsorb on the surface. The air release mechanism can quickly release the module from the wall when it is not working. The guide mechanism is used to move the vibration mechanism up and down linearly. Stability retainers are used to prevent unexpected vibrations of the robot body. Compared with the suction cups used in conventional structures, the vibration adsorption method can obtain a stronger and more stable adsorption force, and its environmental adaptability is also better.

To improve the adsorption effect, air pressure adsorption systems can be combined. For example, in the Rise-Rover wall-climbing robot developed by Xiao et al. [45], vacuum adsorption and duct fans are used simultaneously so that the robot can adhere to smooth surfaces and also span grooves. Air pressure adsorption is unsuitable for use in space due to the absence of air.

4.2.3. Clamping Adhesion

Clamping adhesion systems use grippers or other encircling mechanisms to attach a robot to a structure. According to the way the clamping force is generated, clamping methods can be divided into several forms, such as pneumatic clamping, electric clamping, spring clamping, mechanical clamping, and serpentine winding.

Electric clamping relies on the driving force generated by a motor to clamp jaws onto an object. For example, Tavakoli et al. [103] adopted a gripper structure in the 3DClimber pipe-climbing robot. The gripper consists of two unique multi-fingered V-jaws, a brushless DC motor, left and right ball screws, and two linear guides. Force sensors and strain gauges are installed on the jaws, which can sense their clamping force and deformation in real time. Chen et al. [104] adopted a humanoid embracing structure in the EVOC-1 climbing robot. The embracing device is composed of three joints, three link mechanisms, a torsion spring, and other components. The drive motor causes the push rod to push the root joint to make a circular motion around the frame of the driving part.

Spring clamping relies on the force of an adjusting nut and spring. For example, the WRC^{2}IN-I robot [37] adopts a pantograph attachment device to bring it close to a steel bridge cable. The device consists of ball screws, pantographs, springs, wheels, brackets, ratchets, and handles, and is similar to the pantograph mechanism of a train. When the handle is rotated, it rotates a double-helix screw so that the left and right sliders on the screw move to both sides, and the attachment mechanism is brought close to the cable via the action of the connecting rod. The WRC^{2}IN-II robot [40] uses a spring clamping method to attach to steel bridge cables. A handle is used to adjust the clamping force of the spring.

Mechanical clamping relies on the force of a mechanical structure. Sun et al. [41] used a pressing mechanism in a light-pole-climbing robot that consists of a handle, a wedge-shaped extrusion block, a clamping block, a connecting rod, and rubber teeth. When the handle is rotated, the wedge-shaped extrusion block is moved up and down by the thread at the front end of the handle so that the clamping block moves to the right and the rubber teeth clamp firmly to the wire rope.

The clamping attachment method can be easily adapted to slender rod-shaped objects, such as beams, columns, pipes, and trees. However, it is not suitable for flat objects.

4.2.4. Claw Grasping Attachments

Insects and arthropods often use their thorny feet to climb natural or man-made structures. The claw grasping method is a bionic attachment method that uses a claw-thorn structure to anchor to the surfaces of relatively rough objects, such as brick walls, tree trunks, and rock walls.

The claw grasping method was firstly applied in the Spinybot climbing robot [105]. Spinybot uses cockroach-like barbed feet to climb hard, flat surfaces such as concrete and brick walls. Later, Haynes et al. [106] also adopted a similar barbed structure in the RiSE robots. The barbs allow climbing of both hard and soft objects, such as blankets and cork. Lynch et al. [107] adopted a RiSE-like claw-thorn structure in the DynoClimber wall-climbing robot. Ji et al. [108] developed a four-legged robot based on flexible pads with claws that has the ability to climb on rough vertical surfaces. Each pad consists of ten toes, each separated in a radial form. Lam et al. [17] used an omnidirectional claw-thorn mechanism in Treebot composed of four claws. Each claw consists of two phalanges. The tip of each phalanx is equipped with a sharp surgical suture needle, which can penetrate the object being climbed. Under the action of the linear motor and spring, a link mechanism is used to clamp and loosen the clamping jaw. The gripper has a wide curvature, can climbing various tree species, and can clamp the surface of an object using a spring without requiring electricity, providing a good energy-saving effect. Xu et al. [109] used a four-claw gripper with a cross structure in a climbing robot. Each gripper is composed of two pairs of small hooks with a certain elasticity, so that the gripper can grasp rough wall surfaces with improved stability. Liu et al. [110] designed a barbed, bipedal, wall-climbing robot by imitating a known barb structure. The robot has a pair of bionic, spiny, flexible claw feet. Each foot consists of two spiny claws, a spring, a servo, and a cam mechanism. The movement of the cam mechanism is controlled by a steering gear to realize clamping and loosening of the two claws. In the LEMUR robots developed by Parness et al. [111], a ring-shaped micro-thorn gripper is used. The ring gripper is composed of 16 finger-shaped thorns, which are designed in a layered structure to adapt to the surfaces of objects of different scales. Inspired by the micro-thorn structure of the LEMUR robots, Li et al. [112] designed a similar annular micro-thorn claw grasping mechanism. The claw structure consists of 160 flexible micro-thorns evenly distributed on 16 brackets. Liu et al. [113] adopted a barbed wheel in the Tbot wall-climbing robot. The robot consists of two driving wheels and a flexible tail. Each driving wheel is composed of eight layers of thorns, and a partition is installed between the connected thorns. Each wheel thorn piece contains four thorn claws connected to the wheel hub via flexible suspension. This structure enables Tbot to attach to rough walls and attain a high climbing speed. In the six-legged wall-climbing robot developed by Han et al. [114], twelve gripping spiny feet are used to allow the robot to crawl in any direction on a rough wall.

The claw grasping method can adapt well to rough surfaces and does not require power when static. Hence, it is energy-efficient but has difficulty adapting to particularly smooth surfaces such as glass.

4.2.5. Adhesive Adsorption

Adhesive adsorption systems imitate climbing animals such as geckoes or tree frogs, and are divided into dry adhesion and wet adhesion systems. Dry adhesion relies on the van der Waals force between molecules to attach the robot to a surface. Wet adhesion relies on surface tension and the capillary and viscous forces between liquids to adhere a robot to the surface of a wet object.

Dry adhesion. Borijndakul et al. [115] briefly reviewed the characteristics of bio-inspired adhesive foot microstructures used on the climbing robots for smooth vertical surfaces, namely spatula-shaped feet and mushroom-shaped feet. Kalouche et al. [116]

developed the ACROBOT climbing robot for inspecting equipment racks in the International Space Station. A synthetic gecko-like cushion is used to adhere to surfaces, which is composed of a suspension layer and an oriented adhesive layer. The suspension layer conforms to rough surfaces to compensate for small misalignments of the cushion. The oriented adhesive layer contacts the surface of the object to generate van der Waals forces. Murphy et al. [117] used a dry elastomer adhesive as the adhesion material in the first-generation Waalbot wall-climbing robot. However, dry elastomer adhesives lose their grip when contaminated, causing the robot to fall. Later, a great improvement was made in the second-generation Waalbot II. An imitation gecko-fiber-hair adhesive pad is used as the sole adhesion material, and a sticky autonomous recovery mechanism is used so that the robot can reliably adhere to smooth or near-smooth surfaces. In the first-generation spider-like robot Abigaille-I developed by Menon et al. [118], a synthetic dry adhesive pad is used as a foot pad to adsorb to smooth surfaces. The second-generation lightweight climbing robot Abigaille-II developed by Li et al. [119] adopted a plantar structure composed of adhesive patches. The plantar patch has microhairs with mushroom-like caps attached to the tops of millimeter-scale flexible posts, allowing them to adhere to smooth surfaces. Henrey et al. [120] used a layered dry adhesive as a foot-pad material in the third-generation hexapod bionic wall-climbing robot Abigaille-III. The layered dry adhesive is composed of a rigid substrate, a polydimethylsiloxane (PDMS) macro-pillar array, and a micro-pillar array. Three-layer materials are bonded by silica gel, which can attach to smooth and uneven surfaces. Yu et al. [121] developed a robot that can crawl stably on a flexible surface in microgravity with the help of gecko-inspired toe pads. The adhesive pads are based on the microstructure of the dry-adhesion polyvinyl siloxane (PVS) material. Liu et al. [122,123] used adhesive foot pads in the climbing robots AnyClimb and AnyClimb II. Wang et al. [124] adopted an attached foot pad based on thermoplastic adhesive (TPA) bonds in the ThermsBond climbing robot. The rheological properties of TPA give it a large payload capacity, making it useful for various flat surfaces and complex vertical terrain. Osswald et al. [125] used a hot-melt adhesive (HMA) technique to achieve a new type of autonomous robotic climbing. HMA is an economical solution to improving adhesion that acts by controlling the material temperature. The robot is equipped with servo motors and thermal controls to actively change the temperature of the material, and the coordination of these components allows the robot to walk against gravity at a relatively large bodyweight.

Wet adhesion. He et al. [126] designed and fabricated a combination of electroformed and soft-etching technology by analyzing the way that stick insects climb vertical surfaces using their smooth foot pads. A wet adhesion pad with a novel microstructure was applied to a prototype six-legged wall-climbing robot, and a good adhesion effect was achieved. In the climbing robot developed by Wiltsie et al. [127], a novel adhesion effect based on a magnetorheological fluid was used. Magnetorheological fluids are novel “active” or “smart” fluids composed of micron-sized iron particles suspended in an inert oil, and have controllable fluidity. They exhibit low-viscosity Newtonian fluid properties in the absence of an external magnetic field, while they act as a Bingham fluid with high viscosity and low fluidity in an external magnetic field. There is a corresponding relationship between the viscosity of the liquid and the magnetic flux. This conversion consumes low amounts of energy, is easy to control, and has a rapid response.

Adhesive adsorption methods, whether dry or wet, do not require an energy supply. Their disadvantage is that the adhesion force is small and, when the adhesive pad is contaminated, the adhesion effect is greatly reduced or absent, so these methods are unsuitable for outdoor use.

4.2.6. Electrostatic Adsorption

Electrostatic adsorption methods cause the robot to adsorb to an uncharged surface based on the principle of electrostatic induction. Wang et al. [128] used electrostatic adsorption technology in a thin and flexible climbing robot designed for narrow gap detection in industrial equipment. The robot consists of a forefoot and a torso. The forefoot is composed of two short adsorption electrode films and a driving motor film, and the torso is composed of a long driving electrode film and a short adsorption electrode film. Wang et al. [129] proposed an inchworm-like robot composed of flexible printed circuit films for the inspection of narrow gaps in large machines such as generators in power plants. It uses electrostatic adhesion and electrostatic thin-film actuators to achieve a structure with low height. Li et al. [130] used an electrostatic attachment pad for adsorption in a crawler-type wall-climbing robot. It has the advantages of strong adaptability to various walls, a relatively light weight, and a simple structure. Gu et al. [131] used an electro-adhesion technology in a soft climbing robot to adsorb on the surfaces of wood, paper, glass, and other objects. Attachment and detachment of the robot are realized by adding and cutting off the voltage to the electro-adsorption feet. Electrostatic adsorption is suitable for smooth and clean surfaces, but the adsorption force is small and the load capacity is weak.

4.2.7. Hybrid Adhesion

Hybrid adhesion methods use a variety of adhesion methods to enhance a robot's adhesion abilities. Xu et al. [132] designed a wall- and glass-climbing robot that uses three attachment methods: micro-thorn grasping, viscous adsorption, and vacuum adsorption. When climbing on rough walls, the robot adopts micro-thorn grasping and vacuum adsorption methods, and when climbing on smooth glass surfaces, it adopts viscous adsorption and vacuum adsorption. Liu et al. [133] imitated the climbing and adsorption functions of flies and larval fish. The attachment device of the robot is composed of a grasping mechanism, an adhering mechanism, and an adsorption mechanism. The gripping mechanism consists of four ratchets for gripping particles on rough walls. The suction mechanism consists of a turbofan, suction cups, and flexible skirts, which can provide suction for the robot during the entire motion cycle. The adhesion mechanism consists of an adhesive material that provides adhesion to a wall surface. Inspired by the climbing strategy of geckos, Ko et al. [134] proposed a crawler motion solution that simultaneously uses static electricity, elastomer adhesion, and tail force in a climbing robot. Hybrid adsorption can be suitable for different surfaces, but the adsorption device requires a complicated structure.

4.2.8. Other New Adhesion Methods

In recent years, with the development of new materials and technologies, some new adhesion methods have emerged. Huang et al. [135] developed a boronate polymer hydrogel and applied it to a climbing robot. It can rapidly switch between bonded and non-bonded states in response to mild electrical stimulation between 3 V and 4.5 V. William et al. [136] adhered a robot to surfaces by means of gas lubrication generated by vibration. This robot uses an eccentric rotor motor (ERM) as a suction device. This motor can drive a 14 cm diameter floppy disk to generate 200 Hz vibrations. With these vibrations, a low-pressure gas film with a thickness of several hundred microns is created between the robot and the surface, providing the robot with sufficient adhesion. Compared with other climbing robots, the robot is lighter in weight, lower in cost and power consumption, and has a great application space in high-altitude operations. Since these new attachment technologies are still in the process of exploration, their adhesion performance remains to be further verified.

All of the above adhesion methods have their advantages, disadvantages, and applicable scopes. A performance comparison is provided in Table 1.

Table 1. Comparison of various robot adhesion methods.

Method	Advantages	Disadvantages	Applicable Scope	Representative Products
Magnetic adsorption	Large adsorption force, permanent magnet does not need electricity	Magnets are generally heavy, which increases weight and reduces the load capacity	Ferromagnetic materials	Omniclimbers, Minibobot-W
Air pressure adsorption	Large adsorption force, easy to control, regardless of materials	High energy consumption, noise, large size, movement delay, poor safety	Flat, smooth non-porous and non-cracked surfaces	W-Climbot, Vortexbot, EJBot, UOTWCR, Rise-Rover
Clamping adhesion	Low energy consumption, no noise, strong load capacity	Clamping directivity	Slender objects such as rods or tubes	3DClimber, WRC^{2}IN
Claw grasping	No energy consumption, no noise, strong load capacity	Damages soft objects	Rough objects with bulges or pits	Spinybot, DynoClimber, Tbot, Treebot LEMUR
Adhesive adsorption	No energy consumption, no noise	Weak load capacity and slow movement speed	Smooth objects	Abigaille-III, AnyClimb, Waalbot ThermsBond
Electrostatic adsorption	Low weight, small dimensions, low energy consumption, and no noise	Low load capacity, slow speed, sensitivity to surface conditions involving dust	Uncontaminated and uncharged objects	[128,129]
Hybrid adhesion	Good comprehensive performance	Complex structure	Adapts to a variety of environments	[132–134]

4.3. Locomotion Modes

Locomotion mechanisms enable a robot to move up and down or side to side on the inner and outer surfaces of climbed objects. Locomotion modes can be divided into active and passive types. The passive type is generally rope-driven and mainly relies on external power, such as a hoist and winch, to move a robot via traction of a cable. The robot itself does not provide power. According to the movement mechanism, active types can be divided into wheeled, legged, tracked, inchworm, and hybrid types.

4.3.1. Rope-Driven Locomotion

Rope-driven climbing robots are tethered to a rope that is pulled by a winch. Fujihira et al. [137] developed a rope-driven steel-cable-climbing robot for detecting cables in suspension bridges under strong wind conditions. The robot relies on the coordinated action of a wire rope and ascender to move up and down. Seo et al. [138,139] designed a parallel climbing robot that consists of a measuring device and two lifters. It can carry heavy loads for surface work in large workspaces. Lee et al. [67] designed a wire-rope-driven parallel robot system for offshore wind turbine maintenance. The robotic system consists of a mobile platform and two manipulators. The mobile platform sets four hoists at the four corners of the robotic system for the climbing of wind turbine towers or blades. Each hoist contains a pulley that controls the length of the wire between each hoist and the nacelle to achieve positional and orientation control of the mobile platform. Begey et al. [140] designed a three-cable-driven parallel robot called PiSaRo2, which consists of three cables, three pulleys, three winches, and an end effector. The robot can be raised or lowered via a winch. Seo et al. [141] designed a parallel robot driven by double hoisting cables. The robot consists of two lifters and two rope-measurement sensor structures. Unlike other cable-driven parallel robots that require an external winch structure, this robot requires only two ropes, as the traction pulleys of the hoist allow the robot to climb using the ropes.

Rope-driven climbing robots can be large, carry heavy loads, and have good climbing speed, stability, and safety. Their disadvantage is the need for a winch-and-pulley lifting system, which reduces their flexibility and increases manufacturing and installation costs.

4.3.2. Wheeled Locomotion

Wheeled climbing robots are inspired by automobiles. Wheels are one of the most common locomotion modes and have been applied to many climbing robots. Wheeled climbing robots commonly have three [94,142], four [52,62], or six wheels [12]. The cable-climbing WRC^{2}IN-I robot adopts three sets of wheel-drive devices that are evenly distributed in the circumferential direction at 120° angles to each other. The drive device is composed of a DC brushless deceleration motor, a toothed clutch, a bevel gear, a spur gear, an arc wheel, and a support frame. In the power-on state, the clutch works, the motor drives the arc wheel to rotate through the bevel gear and spur gear, and the robot climbs using the friction between the wheel and cable. Zheng et al. [142] designed a lightweight wheeled cable-climbing robot composed of three-wheeled climbing modules enclosed by hinges. Two of the three modules are drive modules, while the other is a passive module. Each module is fitted with two wheels and spring dampers for easy adaptation to ropes of different diameters. Wheeled climbing robots have high speeds, continuous movement, simple structures, simple controls, and low energy consumption; however, their obstacle negotiation ability is weak.

4.3.3. Tracked Locomotion

Tracked climbing robots are inspired by tanks. They have a large contact area, fast speed, continuous movement, and strong obstacle negotiation ability. They are widely used in scenarios where speed, continuous movement, and obstacle negotiation ability are required simultaneously. Cho et al. [40] designed a two-module tracked-type cable-climbing robot called MRC^{2}IN-II for the inspection of suspension bridges. The robot consists of two tracks, two safety landing devices, and an attachment device enclosed by bolts. Nguyen et al. [59] developed a roller-chain-like steel-bridge-climbing robot with a tank-like shape for the inspection of municipal steel bridges. The robot consists of two rows of roller chains and a support frame. The robot controls the contact angle between the roller chain and steel bridge via a linear reciprocating drive device that can adapt to bridge surfaces with various shapes. Sun et al. [41] adopted a tracked pole-climbing robot. The drive device is composed of two sets of chain drive mechanisms arranged opposite to each other and a DC deceleration motor. The motor drives the chains on both sides to rotate through the gear transmission, and the robot's climbing action is realized by the friction between the rubber teeth on the chain and the wire rope. Unver et al. [143] developed a tank-like climbing robot called Tankbot. It weighs only 115 g, can carry 300 g on ordinary painted walls, can cross obstacles up to 16 mm in diameter, and can perform vertical wall-to-ceiling conversions. Liu et al. [144] designed a tracked-type wall-climbing robot named SpinyCrawler. The robot is driven by a roller chain driven by a motor. It can climb on rough walls, such as vertical concrete walls, gravel walls, sandpaper walls, and brick walls, and can also traverse brick ceilings. The disadvantage of tracked climbing robots is that turning is not easy to control.

4.3.4. Legged Locomotion

Legged climbing robots are inspired by the limbs of humans or animals. Legged robots can be divided into three types, series, parallel, and series-parallel hybrid, and may be two-, four-, six-, or multi-legged. For example, the InchwormClimber robot [145] adopts a two-legged climbing structure. The robot consists of two links and three revolute joints. The robot relies on a magnetic wheel to adsorb on a surface, relies on a motor to realize two-legged movement through the belt drive, and completes up-and-down climbing motion according to a certain gait sequence. Parness et al. [146] developed a four-legged climbing robot called LEMUR 3 consisting of a torso, four legs, and four grippers. Each leg has seven degrees of freedom and can freely climb lava caves and solar glass panels in outer space. Bandyopadhyay et al. [147] designed a quadruped climbing robot called Magneto, which consists of 3-DOF actuated limbs and a 3-DOF compliant magnetic foot. It can change its structure and navigate on any slope, as well as through thin beams with different spacings. To increase stability and payload, some climbing robots use six-legged structures, e.g., DIGbot [22] and Abigaille-III [120]. The advantages of legged climbing robots are that they can use a variety of climbing gaits, have strong environmental adaptability, and have a strong ability to overcome obstacles. However, they require complex control systems.

4.3.5. Inchworm Locomotion

As their name suggests, inchworm-style climbing robots are inspired by inchworms. These robots usually consist of two separable parts: one fixed, and one that slides or rotates. They can achieve long-distance climbing tasks. Zheng et al. [26] developed an inchworm-style cable-climbing robot dubbed CCRobot. The robot consists of a clamping module and a parallel operating arm. The clamping module is divided into upper and lower parts. The parallel operation arm consists of upper and lower platforms and three sets of 3-RPS (Revolute–Prismatic–Spherical) articulated arms. The upper platform and upper arm are connected by a ball joint, the lower platform and lower arm are connected by a rotating joint, and the upper and lower arms are connected by a moving joint, and are all driven by a DC motor. Sun et al. [148] designed an inchworm-style climbing robot for cleaning the glass on high-rise buildings. The robot consists of two mutually perpendicular rodless cylinders, a rotary cylinder, four *Z*-axis lift cylinders, and sixteen suction cups. The suction cups stick to the glass and autonomous climbing is achieved through the alternating rotation of two rodless cylinders. The advantages of inchworm-type climbing robots are that their structures and controls are relatively simple. Their disadvantages are discontinuous movement and slow speed.

4.3.6. Hybrid Locomotion

Hybrid climbing robots combine the advantages of two or more forms of climbing structures and can adapt to more complex climbing environments. Mguyen et al. [58] designed a wheel-leg hybrid steel-bridge-climbing robot consisting of a torso and two legs. When moving on a flat surface, the two legs are fixed in position and mainly move in a wheeled manner. When crossing obstacles, one of the legs is fixed and the other leg can be extended to move in a walking manner. The pipe-climbing robot designed by Han et al. [13] adopts a 4-DOF wheel-leg climbing structure. The robot consists of two drive modules and a connecting arm. On smooth pipes, the robot uses a wheeled climbing mode to move quickly. When it needs to overcome obstacles such as elbows or T-joints, it switches to a legged climbing mode. Moon et al. [149] used a combination of the rope-driven mode and guide-rail mode in a maintenance robot system to allow it to climb the facades of high-rise buildings.

Hybrid climbing robots have strong environmental adaptability and good comprehensive performance; however, they require a relatively complex structure. The advantages, disadvantages, and performance of the various locomotion modes are compared in Table 2.

Table 2. Comparison of locomotion performance.

Locomotion Mode	Advantages	Disadvantages	Applicable Scope	Representative Robots
Rope-driven	Strong load-carrying capacity, fast, high degrees of stability and safety	Requires a winch, limited movement, high manufacturing and installation costs	Scenarios requiring heavy loads	PiSaRo2
Wheeled	Fast, continuous movement, simple structure, simple control, low energy consumption	Weak obstacle-negotiation ability	Flat objects	WRC^{2}IN-I UT-PCR WCR-Eto
Tracked	Large contact area, fast, continuous movement, strong obstacle-climbing ability	Complex structures, difficulty turning	Scenarios with obstacles	Tankbot, SpinyCrawler, MultiTank, Rise-Rover
Legged	Environmental adaptability, ability to overcome obstacles	Complex structure, complex control, discontinuous movement, slow	Scenarios with substantial obstacles	InchwormClimber, DIGbot Climbot
Inchworm	Simple structure, simple control, high safety factor	Discontinuous movement, slow	Scenarios with small obstacles	CCRobot, CROC, Treebot, Pylon-Climber, EJBot
Hybrid	Environmental adaptability, good comprehensive performance	Complex structure	Complex climbing environments	OmniClimber

4.4. Security Mechanisms

In an emergency such as a sudden power failure, it is critical that a climbing robot not fall from the climbed object. So, devices for safe landing and recovery are required. Most climbing robots are driven by DC gear motors or servo motors. Such motors often have a self-locking mechanism such as a worm gear, which acts as a safety feature in the event of a power failure. In addition, some robots use special safe-landing devices. WRC^{2}IN-II [40] adopts a safe-landing device composed of a timing belt, a pulley, spur gears, a disc damper, a reverse braking device, and a support shaft. When the robot descends due to a loss of power, the synchronous belt drives the pulley, spur gear, and internal device of the disc damper to rotate. The reverse braking device is fixed when there is a loss of power, so that the external device of the disc damper is fixed. The disc damper contains viscous silicone oil that damps energy during the robot's descent, so that it can land safely. If the robot gets stuck on the cable, the robot can use a clutch mechanism to allow it to return safely to the ground. Xu et al. [33] used a gas-damper safe-landing device with a sliding rod mechanism in a cable-climbing robot. The safe-landing mechanism consists of a cylinder and a slider mechanism. A crank is fixed to the driveshaft by a one-way clutch. When the robot climbs, the one-way clutch is released. As the robot slides down, a drive wheel drives the slider–crank mechanism via the clutch. The rotational motion of the drive wheel is converted into reciprocating motion of the piston in the cylinder. The gas in the cylinder is alternately inhaled or discharged through nozzles arranged on the bottom wall of the cylinder, forming a gas damper that consumes the kinetic energy of the robot. The size of the nozzle can be adjusted to obtain different damping rates to control the landing speed of the robot. Gui et al. [150] used active and passive anti-fall devices in a tree-pruning robot to prevent it from falling to the ground. The passive anti-falling mechanism uses only friction forces and robot gravity force to maintain a hold on the tree trunk. The active anti-fall mechanism adjusts the distance between the wheel and trunk using a stepper motor and a lead screw nut unit. While safe-landing and recovery devices can improve the safety factors of robots by ensuring that they can be recovered after a power failure, they also increase their weight.

4.5. Control Methods

The control system is the core of a climbing robot. Its main task is to control the robot's actuator to complete specified movements and functions according to the user's work instructions, the robot's control programs, or feedback from sensors. The control system mostly adopts a master–slave system composed of two parts: a ground monitoring station and a robot controller. The ground station is usually composed of a portable PC, smartphone, remote control, and game handle. The robot controller mostly comprises microprocessors or single-board computers such as an Arduino, Raspberry Pi, MCS51, PIC, STM32, or PLC. Because climbing robots often need to travel long distances, the ground station and robot controller often use wireless communication methods such as Bluetooth and WiFi. A few robots with short travel distances directly use RS232 or USB for communication. Tavakoli et al. [103] used a wired control system in the 3DClimber robot. The control system consists of a host computer and a controller, which are connected through USB and can send commands and receive sensor information. The controller adopts the CANopen protocol for communication, and controls the position, speed, and torque of each AC or DC motor. Sun et al. [41] adopted a two-layer wireless control system in a pole-climbing robot. The control system consists of an STM32 microprocessor, a wireless signal transmitter, and a wireless graphic transmitter. The WRC^{2}IN cable-detection robots adopt a three-layer wireless control system that consists of a remote portable visual monitoring platform, a master controller, and a slave controller [37]. The monitoring platform is used to issue commands and receive display information. The master controller is used to store the robot's pose state and sensor information and communicate with the monitoring platform. The slave controller is composed of a single-board computer (SBC), which is used to control the motors. The monitoring platform and master controller use the Xbee mode to communicate wirelessly, and the master and slave controllers use the CAN bus mode to communicate. The Rise-Rover climbing robot adopts a three-layer wireless control strategy which consists of a user layer, a middle layer, and a bottom layer [45]. The user layer is an Android mobile phone platform, which is mainly used as a user interface for remote control and video monitoring. The middle layer is an embedded Linux platform, which mainly handles peripheral devices, such as cameras and NDT devices. The bottom layer is controlled by an Arduino controller, which mainly deals with real-time control of the motor and PID control of air pressure.

Apart from the hardware components, some robots also use software to realize a human–machine interface and improve the robot's autonomy. In the Waalbot II robot [117], a two-level motion planner is implemented, so that transitions between locally flat regions are identified using the upper planner and the specific robot trajectory is planned using an A* search algorithm. To implement autonomous climbing in the Climbot robot [10], a truss modeling and recognition system has been proposed. The system adopts a Truss Segmentation Pouring Algorithm and a Truss Parametric Expression Algorithm to recognize truss-style structures. Li et al. [151] developed a robotic system for the automatic inspection of weld defects in spherical tanks. The robot adopts a weld-line tracking method based on deep learning, as well as an optimal path-planning method for traversing all the weld lines of a spherical tank.

4.6. Operating Tools

Climbing robots are mainly used to carry tools to conduct various tasks, such as inspection, cleaning, spraying, welding, maintenance, and pruning. These tools may include cameras, manipulators, nondestructive testing equipment, laser-cleaning equipment, and spraying equipment. Some work tools are off-the-shelf, while others require customization. The designers must consider how these tools are carried by the robot and their impact on climbing performance. Xu, et al. [36] installed two cameras and a nondestructive testing device on a cable-climbing robot to carry out cable inspection. Cho et al. [40] installed four cameras and a nondestructive testing device in the MRC^{2}IN suspension bridge cable inspection robot. In the glass curtain wall inspection robot developed by Liang et al. [152], an operating arm is used to detect the firmness of the glass installation. Huang et al. [153] designed a multifunctional pruning and crushing end effector for automatic pruning of fruit trees. The Model-IV cable maintenance robot [36] uses four working modules for grinding, cleaning, spraying, and winding. Lee et al. [53] used a window-cleaning device in a wall-climbing cleaning robot. Tools will increase the weight of a robot and change its center of gravity, which will affect its climbing performance.

5. Typical Climbing Robots

In the past decade, a large number of climbing robots have been developed. Table 3 presents a list of some typical climbing robots according to the above-mentioned classes. Some typical robotic prototypes without specific names are not listed.

Table 3. List of climbing and operating robots.

Robot Name	Category	Adhesion	Locomotion	Controller	Tools	Country	Year
UT-PCR	Pole-climbing	Clamping	Wheeled	Unknown	Camera, washing devices	IR	2011
Climbot	Pole-climbing	Clamping	Legged	Accelnet	Grippers, Camera	CHN	2011
EVOC-1	Pole-climbing	Clamping	Inchworm	Unknown	Unknown	CHN	2019
Snake-like robot	Pole-climbing	Clamping	Inchworm	Arduino	Unknown	CHN	2020
DIGbot	Tree-climbing	Claw	Legged	SBC	Unknown	US	2010
Treebot	Tree-climbing	Claw	Inchworm	Unknown	Unknown	CHN	2011
PylonClimber-I	Pylon-climbing	Clamping	Inchworm	C8051	Unknown	CHN	2017
PylonClimber-II	Pylon-climbing	Clamping	Inchworm	C8051	Unknown	CHN	2018
CROC	Bridge-climbing	Magnetic	Inchworm	Unknown	Unknown	AUS	2014
ARA-I robot	Bridge-climbing	Magnetic	Tracked	Unknown	Camera	US	2019
ARA-II robot	Bridge-climbing	Magnetic	Hybrid	Arduino	Unknown	US	2020
WCR^{2}IN-I	Cable-climbing	Clamping	Wheeled	SBC	Camera, NDT	KR	2012
WCR^{2}IN-II	Cable-climbing	Clamping	Tracked	SBC	Camera, NDT	KR	2014
EJBot	Cable-climbing	Pressure	Wheeled	Arduino	Camera	EGY	2017
CCRobot-I	Cable-climbing	Clamping	Inchworm	STM32	Camera	CHN	2018
CCRobot-II	Cable-climbing	Clamping	Inchworm	STM32	Camera	CHN	2019
CCRobot-III	Cable-climbing	Clamping	Hybrid	SoC	Camera	CHN	2020
CCRobot-IV	Cable-climbing	Clamping	Hybrid	PX4	Camera	CHN	2021
Model-1	Cable-climbing	Clamping	Wheeled	STM32	Camera, NDT	CHN	2012
Model-2	Cable-climbing	Clamping	Wheeled	STM32	Camera, NDT	CHN	2014
Model-3	Cable-climbing	Clamping	Wheeled	STM32	Camera, NDT	CHN	2015
Model-4	Cable-climbing	Clamping	Hybrid	STM32	Grinding devices	CHN	2021
Waalbot II	Wall-climbing	Adhesive	Hybrid	VICON	Camera	US	2011
Minibobot-W	Wall-climbing	Magnetic	Inchworm	C8051	Probe	CHN	2012
W-Climbot	Wall-climbing	Pressure	Legged	Accelnet	Camera	CHN	2012
MultiTank	Wall-climbing	Pressure	Tracked	PIC	Unknown	KR	2013
LARVA-II	Wall-climbing	Pressure	Wheeled	Unknown	Camera	KR	2013

Table 3. *Cont.*

Robot Name	Category	Adhesion	Locomotion	Controller	Tools	Country	Year
Abigaille-II	Wall-climbing	Adhesive	Legged	FPGA	Unknown	CAN	2012
Abigaille-III	Wall-climbing	Adhesive	Legged	FPGA	Unknown	CAN	2014
ACROBOT	Wall-climbing	Adhesive	Inchworm	Baby orangutan	Unknown	US	2014
Rise-Rover	Wall-climbing	Pressure	Tracked	PIC	NDT	USA	2015
Tbot	Wall-climbing	Claw	Wheeled	Unknown	Unknown	CHN	2015
OmniClimber-I	Wall-climbing	Magnetic	Hybrid	STM32	Unknown	PT	2014
OmniClimber-II	Wall-climbing	Magnetic	Hybrid	STM32	Unknown	PT	2016
MARC	Wall-climbing	Magnetic	Tracked	Unknown	Camera	ITA	2017
Vortexbot	Wall-climbing	Pressure	Wheeled	Arduino	Unknown	CHN	2017
LEMUR 3	Wall-climbing	Claw/Adhesive	Legged	VDX-6354	Unknown	US	2017
PiSaRo2	Wall-climbing	No	Wire-driven	RPi	Unknown	FR	2018
AnyClimb-I	Wall-climbing	Adhesive	Inchworm	Unknown	Unknown	KR	2016
AnyClimb-II	Wall-climbing	Adhesive	Inchworm	Unknown	Unknown	KR	2018
Mantis	Wall-climbing	Pressure	Tracked	Arduino	Unknown	SG	2019
UOTWCR-II	Wall-climbing	Pressure	Wheeled	Unknown	Unknown	IRQ	2020
SpinyCrawler	Wall-climbing	Claw	Tracked	Unknown	Unknown	CHN	2020
Ibex	Wall-climbing	Pressure	Wheeled	Arduino	Unknown	SG	2020
GFCR	Wall-climbing	Pressure	Hybrid	Arduino	Roller brush	IN	2022
Clothbot	Cloth-climbing	Claw	Wheeled	Unknown	Unknown	CHN	2012
LEeCH	Various applications	Pressure	Inchworm	Arduino	Unknown	JPN	2019

6. Challenges and Future Research Directions in Climbing Robots

6.1. Challenges Faced

After decades of development, climbing robots have made great progress in terms of adhesion, locomotion, and control methods. However, there are very few climbing robots that have been widely used in the market. The main reason for this is that there are still many unresolved problems and challenges in the development of this technology, as described below:

(1) Multi-environmental adaptation problems. Due to the variety of climbed objects, no climbing robot can achieve stable climbing and complete tasks in various complex unstructured environments.

(2) Application problems. Although hundreds of prototypes of climbing robots have been developed around the world, most of them are still in the laboratory research stage and cannot be adapted to complex industrial and agricultural field environments. Most climbing robots are only equipped with cameras and a few sensors and lack other working tools, which limits their application scope.

(3) Energy supply problems. As a cable-powered robot gains height, the length of the cable increases and, hence, so does its overall weight. Battery-powered robots have a limited life, so continuous research is required to improve battery life.

(4) The issue of autonomy. Most current climbing robots can only work under manual or semi-automatic conditions. It is difficult to achieve autonomous operation due to the complexity of the environment.

6.2. Main Future Research Directions

With the development of new materials and technologies, future research on climbing robots will focus on improving the reliability of adhesion mechanisms, the operability and autonomy of movement, and the development of related operating tools. The main aspects are as follows:

(1) Bionic climbing robots. Bionic design is widely used in product design, architectural design, and other fields. Many animals have strong adhesion and climbing abilities, providing a good reference for research on climbing robots. Researchers study the shape, structure, and function of animals and apply this knowledge to robot design via mathematical modeling, mechanical analysis, digital simulation, virtual simulation, and other means. Bionic design for climbing robots focuses on new bionic materials, bionic mechanisms, attachment methods, and the imitation of gaits.

(2) Modular climbing robots. The modular method is a basic way to solve complex problems. It combines simple modules to form a complex system that is universal, reconfigurable, extensible, and self-healing. As well as their low cost, they are widely used in the development of complex electromechanical systems, such as automated assembly lines and robots. Through modular design, a climbing robot system can be constructed with many of the same or different adhesion modules, motion modules, and control modules. These modules are independent and complete units that can be easily connected or disconnected from each other; thereby, robotic systems with many different purposes and functions can be built.

(3) Intelligent climbing robots. Intelligence means giving robots certain human behaviors and cognitive and decision-making functions so that they can respond autonomously to changes in the surrounding environment. The intelligent design of climbing robots mainly focuses on intelligent control. With the help of various sensors, as well as machine vision, deep learning, and other technologies, a robot can autonomously identify the surrounding environment, automatically plan a movement path, and autonomously cross obstacles.

(4) Lightweight designs. The weight of the robot directly affects its climbing and loading performance, so it should be minimized. The main idea of lightweight design is to use lightweight materials such as high-strength steel, aluminum alloy, carbon fiber, and engineering plastics. Another method is to optimize the structure of the robot through finite element analysis.

(5) Flexible and soft climbing robots. Compared with rigid climbing robots, flexible and soft climbing robots have better environmental adaptability, safety, and human–computer interaction capabilities. Future research on flexible climbing robots will mainly focus on the utilization of flexible materials such as liquid silicone rubber, hydrogels, electroactive polymers, shape memory alloys, shape memory polymers, and liquid metals, as well as liquid actuators.

(6) Hybrid designs. At present, a variety of adhesion and locomotion methods have been developed for climbing robots, each with its own advantages, disadvantages, and adaptability. One main research direction is the hybrid design of multiple adhesion and locomotion methods, so that climbing robots can adapt to complex environments.

(7) Integrated design. Integrated design is a common design method used to improve productivity. The integrated design of climbing robots integrates adhesion devices, mobile devices, control platforms, and operating tools to allow them to complete certain climbing tasks.

(8) Multi-machine collaboration. In large-scale operating environments, relying on single robots is no longer possible. The use of multiple robots can also enhance flexibility, especially in the optimization of resource allocation and scheduling. Research on multi-robot synergy focuses on collaborative perception, collaborative planning, and collaborative control.

7. Conclusions

Climbing robots have good application potential in scenarios that are difficult or dangerous for humans to work in. This paper reviewed the past decade's research on bionic climbing robots designed for climbing vertical structures such as poles, cables, walls, and trees, and discussed some of their applications. Some key aspects, such as conceptual design, adhesion mechanisms, locomotion modes, safety mechanisms, control methods, and operating tools, were explained using examples. The advantages, disadvantages, and applications of each method were compared and analyzed. Finally, the challenges faced by climbing robots and the main future research directions were discussed.

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浙江省人民政府办公厅文件

浙政办函〔2016〕6 号

浙江省人民政府办公厅
关于省一流学科建设名单的复函

省教育厅：

你厅《关于要求公布省一流学科建设名单的请示》(浙教高科〔2015〕138 号)悉。经研究，省政府同意将浙江大学生态学等 98 个学科列入省一流学科(A 类)建设名单，将浙江大学哲学等 232 个学科列入省一流学科(B 类)建设名单。

你厅要会同省级有关部门加强指导，加大统筹支持力度，为省一流学科建设创造条件，加快推进全省高等教育总体水平的提升。

附件:省一流学科建设名单

浙江省人民政府办公厅

2016年1月18日

附件

省一流学科建设名单

一、省一流学科（A类）建设名单（98个）

序号	学　　校	学 科 名 称
1	浙江大学（20个）	生态学
2		机械工程
3		光学工程
4		材料科学与工程
5		动力工程及工程热物理
6		电气工程
7		控制科学与工程
8		计算机科学与技术
9		土木工程
10		化学工程与技术
11		农业工程
12		软件工程
13		作物学
14		园艺学
15		农业资源与环境
16		植物保护
17		畜牧学
18		临床医学
19		管理科学与工程
20		农林经济管理

序号	学校	学科
186	浙江水利水电学院(6个)	电气工程
187		测绘科学与技术
188		软件工程
189		水利工程
190		机械工程
191		土木工程
192	衢州学院(4个)	控制科学与工程
193		机械工程
194		土木工程
195		化学工程与技术
196	宁波大红鹰学院(4个)	计算机科学与技术
197		应用经济学
198		工商管理
199		机械工程
200	浙江越秀外国语学院(1个)	外国语言文学
201	温州肯恩大学(1个)	应用经济学
202	浙江音乐学院(筹)(2个)	艺术学理论
203		戏剧与影视学
204	浙江医学高等专科学校(4个)	基础医学
205		临床医学
206		公共卫生与预防医学
207		药学
208	浙江大学城市学院(3个)	药学
209		工商管理
210		土木工程
211	浙江大学宁波理工学院(3个)	化学工程与技术
212		机械工程
213		土木工程

附件

浙江省一流学科申报表

学 校 名 称 （盖章）：<u> 浙江水利水电学院 </u>

学 科 名 称 ：<u>   机 械 工 程   </u>

申 报 类 型 （**A /B**）：<u>   B   </u>

浙江省教育厅制

2015 年 12 月 5 日

学科简况表说明

1. 师资队伍一栏中：“国家级人才”包括两院院士、国家万人、国家千人、国家青年千人、长江学者、国家杰青基金、新世纪百千万人才工程国家级人选、教育部新世纪人才工程人才、国家教学名师及其他国家级人才。“省级人才”包括省特级专家、省千人、省高校钱江学者特聘教授、“151”人才（重点资助和第一层次，不重复计算）及其他省级人才。人事关系已调出学校的不列入统计范围。

2. 重大项目一栏中：其他国家级重点重大项目包括：“973”项目、“863 项目”等；“省级重大重点项目”包括：省哲学科学规划重大招标课题、省自然科学基金重点和杰青项目、省重大科技专项等。

列入统计范围的项目，主持单位应是本高校。

3. 成果奖项一栏中：国家级成果奖项包括国家自然科学奖、科技进步奖、技术发明奖、全国美展二等奖以上以及其他重大奖项和成果；省部级成果奖项包括教育部科学研究优秀成果奖（科学技术）、教育部教学成果奖、省科学技术奖、省哲学社会科学优秀成果奖等。

除参与完成一列以外，其他各列奖项的要求为第一完成单位。

4. 科研平台一栏中：“其他”还包括：省重点实验室、工程实验室、工程（技术）研究中心、省 2011 协同创新中心、哲学社会科学重点研究基地等。

5.《学科简况表》中统计数据起讫时间为 2010 年 1 月 1 日至 2015 年 9 月 30 日。

一、学科简况表

申报学科名称	机械工程	学科负责人	方贵盛

师资队伍情况（人）	合计（人）	其中：专任教师	正高职称	副高职称	博士学位	海外学习3个月以上	国家级人才	省级人才
	27	27	5	13	9	4		1

重大项目情况（个）	合计	国家自然科学基金重点项目	国家杰出青年基金项目	国家科技重大项目	国家科技支撑项目	国家社会科学基金重点重大项目	教育部人文社科重点重大项目	其他国家重点项目	省级重点重大项目
									1

科研成果情况（项）	类别	总数（第一完成）	其中：特等奖	一等奖	二等奖	三等奖	参与完成个数
	国家级	1			1		
	省部级						

科研平台情况（个）	省部级以上科研平台个数	国家重点实验室	国家工程(技术)研究中心、工程实验室	教育部重点实验室	教育部工程（技术）中心	教育部人文社科基地	国家 2011 协同中心	其他

人才培养情况（人）	在校生总数	博士生	硕士生	本科生	留学生
	291			291	

在国内主要学科排行榜中的排名（注明排行榜名称）	无

二、学校学科规划简况

（介绍申报学校“十三五”学科整体规划简况，本申报学科在学校整体发展规划中的地位。不超过600字）

学校以服务为宗旨，以需求为导向，坚持“特色立足、错位发展、重点突破、以点带面”的原则，优化学科布局，推进学科建设。围绕现代水利和“五水共治”新需求，强化水利工程、水利机械、智慧水利和水利管理的综合应用技术研究，促进水利工程、机械工程、软件工程和管理工程的交叉、渗透和融合，做强水利学科群；瞄准浙江海洋发展战略，加快探索滨海岩土、海洋测绘等研究方向，重点建设土木工程和测绘科学与技术学科；服务国家能源发展战略，积极开展水能、风能和太阳能等应用技术开发，优先推进电气工程学科发展；顺应现代农业发展需求，推动农业节水灌溉、灌排泵站等技术研发与推广，扶持建设农业工程学科。“十三五”期间，力争建设5个省级一流学科，10个校级一流学科；形成以水利水电为特色，土木、测绘、电气、机械、信息、管理等协调发展的学科体系。

在我省大力发展先进装备制造业的基础上，我校的机械工程学科紧密结合学校的行业优势，确立以水利机械为主要研究对象，立足于现代水利、先进制造行业，注重与水利、材料、计算机与环境等学科的交叉发展，开展流体机械传动与测试技术、水利机

械装备数字化设计与控制技术、水利机械装备关键零件成形与表面腐蚀及防护技术等三个方向的研究。我校机械工程学科的建设有利于完善和优化资源配置，既可满足我省水利行业的发展对人才和科研水平的需求，又可促进服务我省制造业的相关学科发展。大力发展机械工程学科符合学校的“十三五”规划，对强化学校办学特色，提升学校综合办学实力有着重要的意义。

三、现有基础

（介绍申报学科现有发展基础，包括人才队伍、科学研究、人才培养、平台建设、社会服务等方面，不超过 800 字）

我校机械工程学科，前身可追溯到 1978 年开设的水利工程机械专业，2014 年被列为校级重点建设学科。本学科依托我校水利行业优势，开展三个特色方向的研究：流体机械传动与测试技术、水利机械装备数字化设计与控制技术、水利机械装备关键零件成形与表面腐蚀及防护技术。该学科现有的发展基础如下：

（1）人才队伍。本学科现有团队成员 27 名，其中正高 5 人、副高 13 人；具有博士学位教师 9 人，在读博士 5 人；省 151 第三层次人才 4 人（其中重点资助 1 人），省专业带头人 3 人，水利厅 325 拔尖人才 1 人。

（2）科学研究。本学科承担各类科研项目 68 项，其中主持国家自然科学基金青年科学基金项目 2 项，省部级项目 25 项；发表论文 108 篇，其中一级期刊 12 篇，SCI、EI 收录 42 篇；获

教学科研成果奖励 9 项，其中国家级教学成果奖二等奖 1 项，省厅级教学科研成果奖 5 项；获国家专利 32 项，其中发明专利 12 项。

（3）人才培养。本学科现开设有机械设计制造及其自动化本科专业和机电一体化技术、模具设计与制造、数控技术和机械质量管理与检测技术等四个专科专业，其中模具设计与制造专业为省特色专业。本专科在校生 1004 名。

（4）平台建设。本学科现建有校级“机械工程研究所”和院级“水利机械研究所”，以及校级“浙江省节水灌溉产品协同创新中心”。现有中央、省财政资助实验室共六个，实验仪器设备总值 1800 余万元，实验面积 8000 平方米。

（5）社会服务。本学科以浙江省实施“五水共治”和大力发展先进制造业为契机，主要面向水利机械行业需求，开展相关科技服务、成果转化工作，先后完成了“杭嘉湖圩区首例竖井式贯流泵装置进出水流道优化分析与应用”、“河道水面漂浮垃圾生态打捞处理技术”、“水库涵管爬管机器人”等省科技厅、省水利厅、水利部杭州机械研究所等单位委托的社会服务项目 15 项，近五年总经费达 500 余万元。项目成果曾获浙江省水利科技创新奖二等奖，研发产品被列入浙江省水利科技推广目录，在全省水利先进适用技术(产品)推介会上得到充分肯定，并受到了分管省领导的高度赞扬。

四、存在问题及不足

（对照一流学科建设目标，分析存在问题与不足，不超过500字）

机械工程学科建设近几年虽然取得了一定的成绩，为我校学科建设的持续、健康发展奠定了良好的基础，但与省内外知名高校一流学科相比，还存在一些问题和不足：

（1）学科建设经费有待于进一步加大投入。我校的机械工程学科建设还处在不断发展过程中，学科内各方向发展还不平衡，围绕学科研究方向的高层次研究平台，如泵阀设计与测试中心、水下检测机器人、金属结构物表面腐蚀及防护、节水灌溉设备研发中心等实验研究平台急需投入经费建设。

（2）学科队伍建设有待于进一步加强。一是需要从国内外引进学科方向带头人和知名学者，带领本学科快速向前发展；二是需要通过加强团队成员的国内外访学和学术交流活动，或到博士后工作站开展专题研究等方式，提升现有学科队伍的整体素质和水平，提升团队成员的协同创新能力；三是需要通过申请高水平的研究项目，发表高水平的研究论文、获取高水平的研究成果来提升学科的整体实力。

（3）人才培养质量有待于进一步提高。在进一步扩大本科生培养数量的基础上，需创新人才培养模式，着重提高学生整体素质和创新能力，切实提高人才培养质量。同时需要通过本学科专业硕士学位授予权的申请，以进一步提升人才培养的质量和水

平。

五、建设总体目标和思路

（包括建设目标、学科发展方向、建设内容与举措及预期标志性成果，不超过 1500 字）

建设目标：我校机械工程学科的建设以创新型人才培养为根本，以高水平学科带头人和师资队伍的建设为重点，以高水平科研产出为突破口，不断开拓创新，强化特色，凝练学科方向，力争在两个建设周期内使我校具有水利机械方向特色的机械工程学科进入全国前 30%。

学科发展方向：结合我校水利行业背景，围绕水利机械，通过合理配置资源、调整学科结构，不断凝练流体机械传动与测试技术、水利机械装备数字化设计与控制技术、水利机械装备关键零件成形与表面腐蚀及防护技术等三个学科方向，使学科特色更加鲜明。紧紧围绕“五水共治”，重点开展水利机械方面的研究，如：泵站内部流动特性分析与结构优化、流体工程节能技术与现代测试技术、水工金属结构设计与制造和金属表面腐蚀及防护技术、基于 3D 打印技术的新型节水灌溉产品研发、疏浚清淤设备设施、水下检测机器人技术等方面的研究，努力实现水利行业“机器换人、自动化减人”。

学科建设内容与举措：（1）人才队伍。采取措施加大内培外引力度，重点是高层次、高学历和高水平学科领军人才的培养和

引进，逐步调整结构提高层次，形成一支方向明确、结构合理，掌握学科前沿发展动向，具有较强科技攻关能力的学科队伍，积极开展国内外访学和学术交流活动。（2）科学研究。围绕水利机械相关的三个学科方向，积极开展具有重要科学意义和应用价值的课题研究，密切与行业、企业的联系，校企联合研发关键或共性技术，加速技术转移步伐，积极培育重大成果。（3）人才培养。通过高水平学科建设，促进专业发展，创新我校 SWH-CDIO 特色人才培养模式，切实提高人才培养质量，着重培养学生的学习能力、实践能力、应用能力和创新能力，积极组织学生参加省级及以上大学生科技竞赛。（4）平台建设。依托学校省部共建平台，争取主管部门、各级财政和学校的投入，集中财力围绕水利机械学科方向建设“泵阀设计与测试中心”、“水利机械制造与金属表面腐蚀及防护技术”、“水下检测机器人”等科学研究平台和基地。加强紧密型校企合作，校企共建研发中心。（5）社会服务。结合行业优势，为浙江省水利机械行业、先进制造企业提供技术开发、人才培训、合作交流等方面服务，加大成果转化的力度。密切与行业、企业的联系，开展“互联网+水利机械技术”服务平台研究，实现资源共享、技术合作，提高水利机械设备设施管护的集约化、专业化和规范化。

经过“十三五”建设，达到预期标志性成果为：

（1）人才队伍

新增省级及以上人才5名以上、学科方向带头人3名、教授5名以上、博士12名以上、海外学习3个月人员15名以上。

（2）科学研究

获得省部级及以上研究项目15项以上，其中国家级项目5项以上；省部级及以上成果5项以上；申请国家专利15项以上，其中发明专利10项以上；三大索引收录论文50篇以上；出版专著、教材10部以上。

（3）人才培养

每年为地方建设培养300名左右，具有较强学习能力、实践能力和创新能力的高素质应用型人才。学生省部级竞赛获奖30项以上。

（4）平台建设

新增“泵阀设计与测试”省部级重点实验室或“节水灌溉技术”工程技术研究中心1-2个。

（5）社会服务

年人均到款额10万以上，年科研成果转化5项以上，五年的社会服务经费达1300余万元。校企共建研发中心3-5个，每年为企事业单位培训员工200名以上，技术咨询和技术服务年人均3-5次。

远期十年目标：在“十三五”建设基础上，进一步加强我校机械工程学科的建设力度，再通过五年的建设，力争到2025年，

使我校具有水利机械方向特色的机械工程学科进入全国前 30%。

附件：《清单目录》

清单目录

1.师资队伍(国家级人才)……………………………………第 13 页

2 师资队伍(省级人才)………………………………………第 14 页

3.重大项目情况…………………………………………………第 15 页

4.科研成果情况…………………………………………………第 16 页

5.科研平台情况…………………………………………………第 17 页

1. 师资队伍（国家级人才）

序号	姓 名	性别	出生年月	学位/学历	专业技术职务	人才类别

2. 师资队伍（省级人才）

序号	姓 名	性别	出生年月	学位/学历	专业技术职务	人才类别
1	郭晓梅	女	1979-11	博士/研究生	副教授	省“151”人才第三层次重点资助

3. 重大项目情况

序号	立项时间	项目来源	项目主持人	项目名称编号	项目经费（万元）	项目等级
1	2012.09	省科技厅	项春	浙江省杭嘉湖圩区防洪减灾能力评估研究（2012C25093）	6+3（配套）	重点软科学研究项目

4.. 科研成果情况

序号	获奖时间	完成人	奖项题目	颁奖部门	奖励等级	主持或参与
1	2014-09	王建军（1/10）	毕业综合实践分类指导全程动态管理模式研究与实践	教育部	国家级教学成果二等奖	主持

说明：教育部教学成果奖在本表填列。

5. 科研平台情况

序号	名称	批准部门	批准时间

教育部办公厅

教高厅函〔2019〕46号

教育部办公厅关于公布2019年度国家级和省级一流本科专业建设点名单的通知

各省、自治区、直辖市教育厅(教委),新疆生产建设兵团教育局,有关部门(单位)教育司(局),部属各高等学校、部省合建各高等学校:

为深入落实全国教育大会精神,贯彻落实新时代全国高校本科教育工作会议精神和《教育部关于加快建设高水平本科教育 全面提高人才培养能力的意见》、“六卓越一拔尖”计划2.0系列文件等要求,全面振兴本科教育,提高高校人才培养能力,实现高等教育内涵式发展,根据《教育部办公厅关于实施一流本科专业建设“双万计划”的通知》(教高厅函〔2019〕18号),经各高校网上申报、高校主管部门审核,教育部高等学校教学指导委员会评议、投票,我部认定了首批4054个国家级一流本科专业建设点,其中中央赛道1691个、地方赛道2363个(名单见附件1)。同时,经各省

级教育行政部门审核、推荐，确定了6210个省级一流本科专业建设点（名单见附件2）。现将2019年度国家级和省级一流本科专业建设点名单予以公布。各地各高校要持续努力，认真实施好一流专业建设“双万计划”。

一、完善专业建设规划。各地各高校要按照一流专业建设条件，完善本科专业建设三年规划，统筹实施好国家级和省级一流本科专业建设计划。要健全专业动态调整机制，做好专业优化、调整、升级、换代和新建工作，加快国家急需专业建设，持续改进专业布局结构。

二、持续提升专业水平。对首批入选的专业建设点，各地各高校要完善支持措施，持续加强建设，不断夯实基础、改善条件。要坚持需求导向、标准导向、特色导向，以社会需求为前提，以一流专业标准为参照，强化专业特色，持续提升专业内涵和建设水平。要以专业认证促进专业高质量发展，落实“学生中心、产出导向、持续改进”的理念，建强用好基层教学组织，形成以提高人才培养水平为核心的质量文化。

三、发挥示范领跑作用。一流专业建设点要以新思想、新理念、新技术、新方法、新标准、新体系为引领，建设一批新工科、新医科、新农科、新文科示范性本科专业，建设一批适应创新型、复合型、应用型人才培养需要的一流本科课程，在专业改革创新、师资队伍、教学资源、质量保障体系等各方面发挥示范辐射作用。

附件：1. 2019年度国家级一流本科专业建设点名单

2. 2019年度省级一流本科专业建设点名单

教育部办公厅

2019年12月24日

附件 2

2019 年度省级一流本科专业建设点名单

序号	高校名称	专业名称	备注
1	浙江水利水电学院	机械设计制造及其自动化	
2	浙江水利水电学院	电气工程及其自动化	
3	浙江水利水电学院	软件工程	
4	浙江水利水电学院	土木工程	
5	浙江水利水电学院	水利水电工程	
6	浙江水利水电学院	测绘工程	
7	浙江水利水电学院	人力资源管理	

一流本科专业建设点
建设报告

学校名称：浙江水利水电学院

学院名称：机械与汽车工程学院

专业名称：机械设计制造及其自动化

专业代码：080202

专业类：机械类

专业负责人：方贵盛

联系电话：13606620840

浙江水利水电学院教务处 制

2021 年 6 月

1. 基本情况

一流专业建设点级别	国家级☐ 省级☑
获批时间	2019 年

2. 本专业新增校级项目、省级及以上奖励和支持情况

类别	序号	项目名称	所获奖励或支持名称	时间	等级	授予部门
教学成果奖	1	教学成果奖	地方行业院校水利机械“一聚焦三突出”育人模式探索实践	2021	校级二等奖	浙江水利水电学院
	2					
	...					
教学名师与教学团队	1					
	2					
	...					
专业建设	1	中外合作本科办学项目	浙江水利水电学院与白俄罗斯国立技术大学合作举办机械设计制造及其自动化专业本科教育项目	2020	省部级	教育部
	2					
	...					
课程与教材	1	一流课程	三维实体建模与设计（方贵盛）	2021	省级	省教育厅
	2	一流课程	工程制图（江有永）	2021	省级	省教育厅
	3	一流课程	电气控制与 PLC（王红梅）	2019	省级	省教育厅
	4	新形态教材建设项目	三维实体建模与设计（方贵盛）	2021	省级	省教育厅
	5		CAXA 数控车编程与图解技能训练（卢孔宝）	2020		机械工业出版社

	6		CAXA 制造工程师编程与图解操作技能训练（卢孔宝）	2020		机械工业出版社
	7	地方标准	《泵站运行管理规程》浙江省地方标准 DB33/T 2248—2020（项春）	2020		
实验和实践教学平台	1	省级工程研究中心	浙江省先进水利装备省工程研究中心	2019	省级	浙江省发展和改革委员会
	2	校企合作基地	杭州娃哈哈集团有限公司	2021	/	紧密合作型
	3	校企合作基地	浙江钱塘机器人及智能装备研究有限公司	2021	/	紧密合作型
	4	校企合作基地	三花汽车零部件有限公司	2021	/	紧密合作型
教学改革项目	1	课程思政教学研究项目	工程类专业课程思政教育教学模式研究与实践（方贵盛）	2021	省部级	省教育厅
	2	2020 年第一批产学合作协同育人项目	新工科专业多方协同育人模式探索与实践（郑高安）	2020	省部级	省教育厅
	3	浙江省本科高校“互联网+教学”优秀案例	《电气控制与 PLC》（王红梅）	2020	省部级	浙江高等教育学会
	4	2019 年第一批产学合作协同育人项目	基于应用型人才培养的《液压与气压传动技术》教学内容和课程体系改革（陈仙明）	2019	省部级	省教育厅
	5	浙江省高等教育“十三五”第二批教学改革研究项目	工程教育专业认证理念下机械类专业工程核心能力培养体系研究（徐高欢）	2019	省部级	省教育厅
	6	浙江省高等教育“十三五”第二批教学改革研究项目	应用型本科高校工程训练教学改革及创新能力培养研究（何理瑞）	2019	省部级	省教育厅
	7	浙江省“十三五”高校虚拟仿真实验教学项目	泵站性能测试虚拟仿真实验（方贵盛）	2019	省部级	省教育厅
	8	浙江省教育科学规划项目	以创新能力培养为核心的教学模式探索与研究（卢孔宝）	2019	省部级	省教科办

教研论文	1	教研论文	面向工程教育认证的应用型本科专业人才培养方案制定（方贵盛）	2020	高教学刊	一般期刊
	2	教研论文	以创新人才培养为核心的实验室开放模式研究与探索(卢孔宝）	2020	实验技术与管理	中文核心
	3	教研论文	基于工程教育认证理念的机械创新拔尖人才培养（方贵盛）	2019	装备制造技术	一般期刊
	4	教研论文	基于创新能力培养为核心的实践教学改革探索与改革(卢孔宝）	2019	浙江水利水电学院学报	一般期刊
学生竞赛获奖（国家级、省级一等奖）	1	“中铁工业杯”第九届全国大学生机械创新设计大赛	基于机器视觉的家庭桌面智能整理机器人	2020	国家级	一等奖
	2	“2020RoboCom 机器人开发者大赛”足球对抗竞赛项目	足球机器人	2020	国家级	三等奖
	3	“2020RoboCom 机器人开发者大赛”足球对抗竞赛项目	足球机器人	2020	国家级	三等奖
	4	RoboCom2019 世界机器智能大赛-全球锦标赛	iLoboke 足球机器人比赛（4X4）	2019	国家级	二等奖
	5	RoboCom2019 世界机器智能大赛-全球锦标赛	iLoboke 足球机器人比赛（4X4）	2019	国家级	二等奖
	6	2019Robocup 机器人世界杯中国赛足球机器人小型组	小型足球机器人	2019	国家级	三等奖
	7	第十二届“高教杯”全国大学生先进成图技术与产品信息建模创新大赛	尺规作图	2019	国家级	二等奖
	8	浙江省第三届智能机器人竞赛	厨房安全卫士	2021	省级	一等奖
	9	浙江省第十八届机械设计竞赛	K-COBOT 智慧厨房协助机器人系统	2021	省级	一等奖
	10	浙江省第十八届机械设计竞赛	剁肉机器人	2021	省级	一等奖

	11	浙江省第二届智能机器人竞赛	智能柔性骑动家庭中央空调管道清洁机器人	2020	省级	一等奖
	12	浙江省第二届智能机器人竞赛	“好帮手”智能家庭整理机器人	2020	省级	一等奖
	13	第十三届“高教杯”全国大学生先进成图大赛机械类建模	尺规绘图、计算机建模、制图基础知识	2020	省级	一等奖
	14	浙江省第七届大学生工程训练综合能力竞赛	势能驱动车	2020	省级	一等奖
	15	浙江省 2019 年第十六届大学生机械设计竞赛	脑电辅助训练多功能电动轮椅	2019	省级	一等奖
	16	浙江省首届智能机器人创意大赛	智能娱乐六足机器人	2019	省级	一等奖
	17	浙江省首届智能机器人创意大赛	基于图像识别智能跟随的多功能老年购物车	2019	省级	一等奖
	18	浙江省首届智能机器人创意大赛	基于图像云识别的智能垃圾桶	2019	省级	一等奖
学生立项项目（国家级）	1	国家级大学生创新创业计划项目	N95 口罩机自动控制系统设计	2021	国家级	
	2	国家级大学生创新创业计划项目	一种多适应性河堤植被修复种植装置的研制	2021	国家级	
	3	国家级大学生创新创业计划项目	小型平面钢闸门面板涂层厚度检测机器人研制	2021	国家级	
	4	国家级大学生创新创业计划项目	智能粥米机器人的研制	2021	国家级	
	5	国家级大学生创新创业计划项目	基于扭力检测功能的数铣卸装刀装置的研发	2021	国家级	
	6	国家级大学生创新创业计划项目	水上漂浮垃圾终结者设计	2021	国家级	
	7	国家级大学生创新创业计划项目	浙水云改装科技有限公司创业计划书	2020	国家级	
	8	国家级大学生创新创业计划项目	闸门钢丝绳自动清洗养护机器人研制	2020	国家级	
	9	国家级大学生创新创业计划项目	基于视觉技术的双色系皮革缝纫装置的研发	2020	国家级	
	10	国家级大学生创新创业计划项目	可延展柔性薄膜显示屏的研制及其在智能防汛救援装备的应用	2020	国家级	

	11	国家级大学生创新创业计划项目	血液透析水处理设备消毒装置关键技术研究	2019	国家级	
	12	国家级大学生创新创业计划项目	智能电动履带灭火机器人系统开发	2019	国家级	
	13	国家级大学生创新创业计划项目	高阶多段变性非圆齿轮驱动的差速泵的设计	2019	国家级	
	14	国家级大学生创新创业计划项目	多功能脑电主动康复训练电动轮椅设计与制作	2019	国家级	
学生授权专利	1	专利	移动式车身清洗装置	2021	实用新型	CN214523711U
	2	专利	替换式洗车装置	2021	实用新型	CN214523719U
	3	专利	一种全能机械制图尺	2021	实用新型	CN214164594U
	4	专利	一种多功能护理床	2021	实用新型	CN213373173U
	5	专利	一种楼梯助行扶手	2021	实用新型	CN213143666U
	6	专利	一种楼梯助行支撑装置	2021	实用新型	CN213250969U
	7	专利	一种轿车子午线轮胎专用隔离剂生产用运输装置	2021	实用新型	CN213112498U
	8	专利	一种全自动旋式草坪垃圾清扫机	2021	实用新型	CN213404367U
	9	专利	一种桥墩壁面清理浮动电动刷	2021	实用新型	CN212742242
	10	专利	一种迫紧式可折叠弯腰辅助升降平台	2021	实用新型	CN212879701U
	11	专利	一种可折叠式弯腰辅助升降平台	2021	实用新型	CN212450508U
	12	专利	一种多功能折叠电动车	2020	实用新型	CN212195780U
	13	专利	一种起蹲助力拐杖	2020	实用新型	CN210120937U

注：数据填报口径为立项时间——2021 年 6 月 30 日

3.本专业建设既定建设举措执行情况

（对照申报书中提及的专业建设和改革的思路及举措等填写执行情况）

一、主要建设思路

1.坚持问题导向原则，实现重点突破和攻关。围绕前期专业建设过程中存在的突出问题和薄弱环节，如课程教学资源建设、校企深度合作推进、学生分析解决复杂工程问题能力提升等，研讨解决措施，实现重点问题一一突破。

2.坚持产出导向原则，深入推进专业认证工作。全面对照教学质量国家标准、工程教育专业认证标准，深入推进课程教学目标达成度测评、专业达成度测评等工作。准备专业认证自评报告，以及其它相关材料的准备工作。

3.紧跟国家形势政策，积极谋划新工科建设。深入高校企业开展调研，获取第一手资料。以现有的流体与水利机械、机械电子 2 个专业方向为基础，根据新工科建设要求，拟调整建设流体与水利机械、智能制造 2 个专业方向，以适应社会发展的需要。

二、主要建设举措

1.加强思想指导，增强培训学习。专业建设离不开专业全体任课教师的支持和配合。工程教育认证产出导向的思想要深入到每一位任课教师的脑海中，并在课程教学和评价过程中予以贯彻落实。学院定期会组织教师进行培训学习，相互交流建设经验等。

2.实施结果导向，优化培养方案。对 2019 版专业人才培养方案实施过程中存在的问题与不足进行分析，并在后续的版本中不断加以完善和解决，逐步达到专业人才培养目标要求。

3.以一流为目标，加强条件建设。一流的专业，需要有一流的师资队伍、一流的课程、一流的实践条件做支撑。近两年，专业紧紧围绕着高层次人才培养、精品课程建设、实验室建设等方面，加大投入力度，确保基础条件能够满足学生培养的要求。

4.多方筹集资金，保障建设经费。争取国家、省厅、学校，以及社会的支持，确保每年的专业建设经费不少于 50 万元，并重点用于学生实习实训、科技创新训练等。

三、执行情况

1.人才培养方案优化及人才培养目标达成度测评

本专业在 2017 版人才培养方案的基础上，2019 年严格按照工程教育认证的思想和要求，对专业人才培养目标、毕业要求、课程体系等进行了系统地修订，对原先的人才培养方案进行了优化调整，其调整思路如图 1 所示。

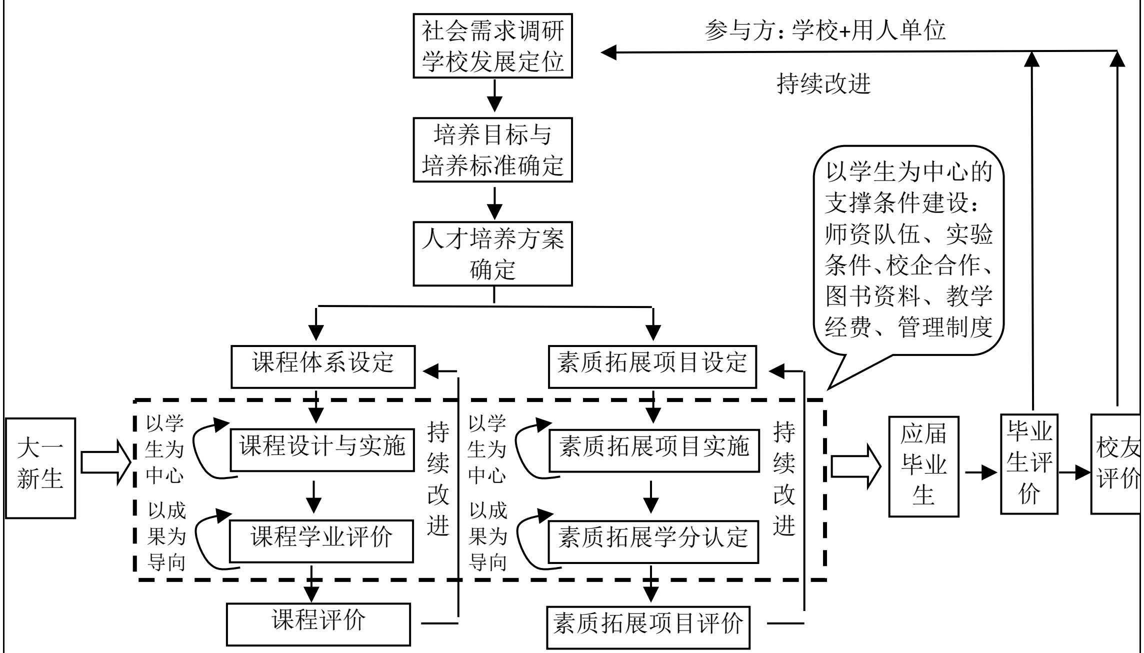

图 1 专业应用型人才培养方案制定思路

首先通过高校、企业、校友调研情况，结合自身的发展定位及特色优势，与企业一同制定专业人才培养目标与人才培养规格标准，并确定专业人才培养实施方案，选择合适的课程教学模式，最后通过质量监督与评价体系，不断持续改进，保证毕业生培养质量能够达到预

先设定的要求。学生则在学校各项教学条件的支持下，通过一门门课程的学习，以及素质拓展项目的训练，一步步提升自己的素质和能力，最终实现自我价值的体现。

（1）专业人才培养目标与定位

本专业培养适应社会主义现代化建设需要，德智体美劳全面发展，具备机械设计、机械制造、自动化的基本知识、基础理论和基本技能，获得机械工程师基本训练，工程意识和工程实践能力强，具有广阔视野、家国情怀、水利精神，具备独立思考和判断能力、自主学习能力、创新能力，较强的表达沟通、人际交往、团队协作能力，能够在机械工程领域以及相关交叉领域内机电产品的设计制造、技术开发、工程应用、生产管理、技术服务等方面工作，适应浙江省乃至全国制造业与水利机械行业产业转型升级需要的高素质应用型人才。

根据工程教育认证标准要求，本专业学生应达到以下五个目标：

1）能够运用数学、自然科学、工程基础知识、专业知识和工程科学的基本原理，研究和解决机械工程相关领域的复杂工程问题。

2）具有较强的机械工程领域技术组织和管理能力，能成为企业或单位的技术或业务骨干。

3）能在团队中担任组织和协助的角色，并能够有效地进行沟通、交流与合作。

4）具备良好的工程素质、职业道德和创新精神，能够在促进经济社会发展的机械工程活动中履行相关责任。

5）过自主学习和继续教育学习，不断获得适应社会可持续发展的能力。

本专业毕业要求和指标项分解如表 1 所示，本专业毕业要求与工程认证要求的通用标准的对应关系如表 2 所示。

表 1　本专业毕业要求和指标项分解

毕业要求	指标点
毕业要求 1—工程知识：能够将数学、自然科学、工程基础和专业知识用于解决机械工程领域复杂工程问题。	1-1 **数学与自然科学知识** 能够将数学及物理、化学等自然科学知识用于复杂机械工程问题抽象模型的建立、计算和求解。
	1-2 **工程基础知识** 能够将力学、电工电子学等工程基础知识用于复杂机械工程问题的解决。
	1-3 **专业知识** 能够将机械设计、机械制造、机电控制等专业知识用于复杂机械工程问题的解决。
	1-4 **知识综合应用** 能够综合应用数学、自然科学、工程基础和专业知识解决机械领域复杂工程问题。
毕业要求 2—问题分析：能够应用数学、物理、力学和工程科学的基本原理，识别、表达、并通过文献研究分析机械工程领域复杂工程问题，以获得有效结论。	2-1 **问题表述** 能够应用数学、物理、力学和工程科学的基本原理，识别机械领域复杂工程问题，并运用图纸、图表和文字等对复杂机械工程问题进行表达。
	2-2 **问题分析** 能够运用机械工程的原理、技术和方法，并通过文献研究，对所表达的机械工程领域复杂工程问题进行分析。
	2-3 **问题总结** 能够综合运用所学知识，对所分析的机械领域复杂工程问题进行归纳总结，并形成有效结论。
毕业要求 3—设计/开发解决方案：能够设计针对机械工程领域复杂工程问题的解决方案，设计满足特定需求的机电液气一体化系统、单元（部件）或工艺流程，并能够在机械系统设计环节中体现创新意识，考虑社会、健康、安全、法律、文化以及环境等因素。	3-1 **需求分析** 能够针对具体的机械领域复杂工程问题，提出总体功能分析，设定合理的技术参数。
	3-2 **方案比较** 能够对机械领域复杂工程问题提出多种技术解决方案，并进行方案比较和分析，选出最合适的解决方案。在设计过程中综合考虑社会、环境、法律、文化、安全等因素，并体现创新意识。
	3-3 **方案详细设计** 能够完成方案的详细设计，并进行原型试验样机的制作与调试。
毕业要求4—研究：能够基于科学原理并采用科学方法对机械工程领域复杂工程问题进行研究，包括设计实验、分析与解释数据、并通过信息综合得到合理有效的结论。	4-1 **设计实验方案** 能够针对机械领域复杂工程问题提出的要求，应用数学、自然科学、机械工程等领域的科学原理，设计、制定实验方案，并正确实施。
	4-2 **分析实验数据** 能够运用合适的分析方法，对实验数据和结果进行分析与处理。

	4-3 **解释实验结果** 能够运用相关专业知识，合理解释实验分析与处理结果，并进行科学评价。
毕业要求 5—使用现代工具：能够针对机械工程领域复杂工程问题，掌握文献检索、资料查询及运用现代信息技术获取相关信息的基本方法的能力；具有综合运用所学科学理论、各种技术手段和现代工程工具分析并解决工程问题的基本能力。	5-1 **信息检索** 能够使用信息检索工具，获取解决机械工程问题的相关资料。
	5-2 **工具应用** 能够运用专业工程软件及技术手册进行设计、模拟和分析复杂机械工程问题。
	5-3 **预测模拟** 能够综合运用信息检索、工程技术与工具，对机械领域复杂工程问题进行预测与模拟，并理解其局限性。
毕业要求 6—工程与社会：能够基于机械工程领域相关背景知识进行合理分析，评价专业工程实践和复杂工程问题解决方案对社会、健康、安全、法律以及文化的影响。	6-1 **实践影响评价** 能够基于机械工程领域工程相关背景知识进行合理分析，评价专业工程实践对社会、健康、安全、法律及文化的影响。
	6-2 **方案影响评价** 能够基于机械工程领域工程相关背景知识进行合理分析，评价复杂机械工程问题的解决方案对社会、健康、安全、法律及文化的影响，并理解机械工程师应承担的社会责任。
毕业要求 7—环境和可持续发展：能够理解和评价针对机械工程领域复杂工程问题的工程实践对环境、社会可持续发展的影响。	7-1 **环境理解** 能够理解针对机械工程领域复杂工程问题的专业工程实践对环境、社会可持续发展的影响。
	7-2 **环境评价** 能正确评价针对机械工程领域复杂工程问题的专业工程实践对环境、社会可持续发展的影响。
毕业要求 8—职业规范：具有人文社会科学素养、社会责任感，能够在机械工程领域工程实践中理解并遵守工程职业道德和规范，履行责任。	8-1 **人文素养** 具备一定的人文和社会科学知识，具有良好的人文艺术和社会科学素养。
	8-2 **社会责任感** 理解个人在历史以及社会、自然环境中的地位，维护国家利益，具有推动社会进步的责任感。
	8-3 **职业道德** 了解机械工程师职业性质与责任，能够在工程实践中自觉遵守职业道德和规范，履行责任。
毕业要求 9—个人和团队：能够在多学科背景下的项目团队或工程实践中，承担个体、团队成员以及负责人的角色。	9-1 **个体责任** 能够在多学科背景下的项目团队中，以及在机电产品或系统的工程实践中，承担个体、团队成员以及负责人的角色。
	9-2 **团队合作** 能够与团队其他成员进行有效合作，共同完成目标任务。
毕业要求 10—沟通：能够就机械工程领域复杂工程问题与业界同行及社会公众进行有效沟通和交流。具备一定的国际视野，能够在跨文化背景下进行沟通和交流。	10-1 **表达沟通** 能够正确撰写技术报告，具备口头与文字表达能力，能与同行及社会公众进行有效沟通与交流。
	10-2 **国际视野** 较好地掌握一门外语，具备一定的国际视野，能够使用技术语言，在跨文化环境下进行沟通与表达。
毕业要求 11—项目管理：在与机械工程专业相关的多学科环境中理解、掌握、应用工程管理原理与经济决策方法。	11-1 **经管知识** 掌握机械工程项目管理所需的基本经济、管理知识。
	11-2 **项目管理** 能够合理应用工程管理原理和经济决策方法进行工程项目组织和管理，并能够控制项目的进度和成本，以保证项目目标的达成。
毕业要求 12—终身学习：具有自主学习和终身学习的意识，具有不断自主学习和适应机械工程领域快速发展的能力。	12-1 **学习意识** 能够正确认识社会及技术的发展与自我发展的关系，理解自主学习和终身学习的必要性。
	12-2 **学习能力** 能够采用合适的方法通过学习不断地适应机械工程领域快速发展的能力。

表 2 专业毕业要求与通用标准的对应关系

标准 / 要求	标准 1	标准 2	标准 3	标准 4	标准 5	标准 6	标准 7	标准 8	标准 9	标准 10	标准 11	标准 12
毕业要求 1	√											
毕业要求 2		√										
毕业要求 3			√									
毕业要求 4				√								
毕业要求 5					√							
毕业要求 6						√						
毕业要求 7							√					
毕业要求 8								√				
毕业要求 9									√			

毕业要求 10										√		
毕业要求 11											√	
毕业要求 12												√

（2）专业课程体系调整思路

1）**优化通识，突出特色，**结合“传授知识、培养技能、塑造人格”的人才培养框架，落实新工科建设理念，按照“专业+X+水利”的思路设置课程（“X 代表”“信息技术”和“管理”等，“水利”代表融合水利行业的专业方向）。

2）学生中心，能力为本。坚持以学生发展为中心，考虑不同成才路径学生的学习需求，注重激发学生学习兴趣和潜能，压缩必修课学时，加大选修课比例，提高学生自主选择空间。

3）**融入创新，丰富载体。**通过整合现有线下教师资源和智慧树、超星、精品在线共享课程等线上教学资源，完善创新创业教育体系，以丰富创新创业类课程模块。推进理实融合，强化课内和课外衔接，落实创新创业教育融入人才培养全过程，促进学生创新精神、创业意识和创新创业能力的培养。

4）课程思政，育人为本。强化课程育人导向的作用，与思想政治理论课同向同行，落实“课程思政”全覆盖。更新教学内容，利用现代技术调整课堂授课方式，推进“翻转课堂”和混合式教学模式，推进研究式、讨论式、互动式教学方法，强化课后辅导，加强形成性考核，推进优质课程建设，着力提高课堂教学的有效性，确保课堂教学质量。

据此，本专业借鉴 CDIO 工程教育模式，以企业真实的工程项目实施为主线，对传统模式下的专业理论课程和实践教学课程进行调整和整合，组建课程模块，构建以层次项目形式的专业课程体系。在专业课程体系制定过程中，积极探索第一课堂、第二课堂、第三课堂之间融合的方式，培养学生的综合能力和素质。本专业建立了机械设计、机械制造、电子电气、机电系统、水利机械、创新设计等六个专业课程群模块，如图 2 所示。以项目的具体实施为主线贯穿专业课教学过程，构建一二三级项目，其中一级项目为专业综合类项目，二级项目为课程群综合类项目，三级项目为课程内项目。通过项目的设计、构思、实施、运作，培养学生创新意识和能力、团队协作精神和工程推理、分析的工程实践能力等。课程与毕业要求达成映射矩阵（部分）如表 3 所示。

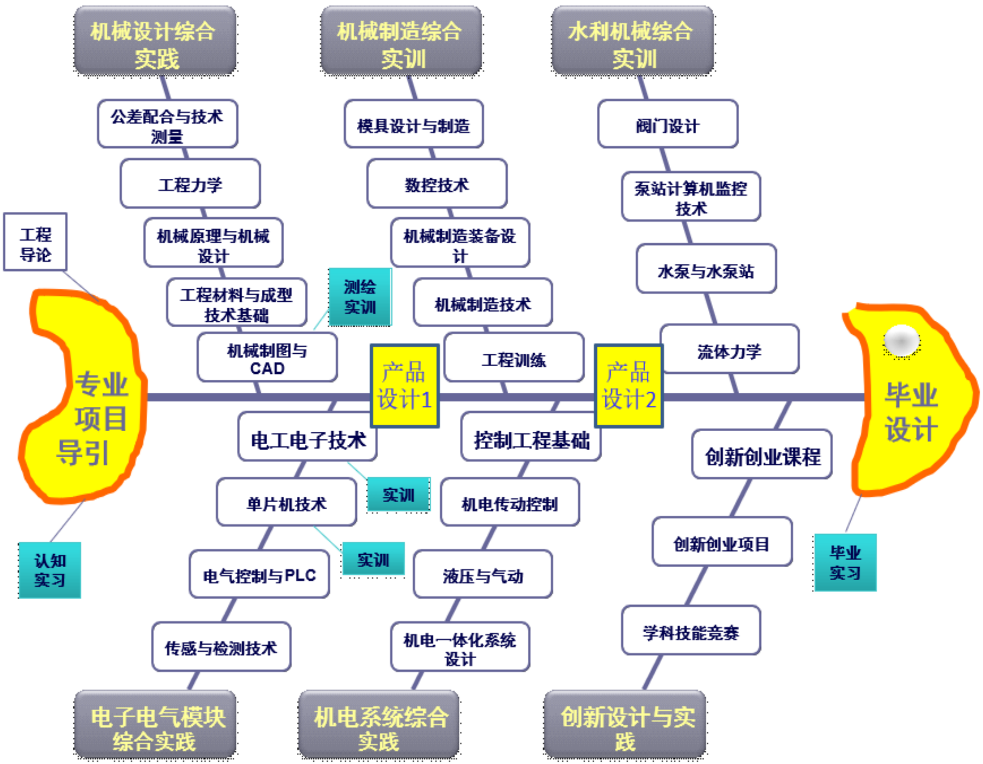

图 2 专业人才培养方案课程体系项目化结构图

表 3 课程与毕业要求达成映射矩阵（部分）

课程名称	要求 1 知识				要求 2 问题			要求 3 方案			……	要求 10 沟通		要求 11 管理		要求 12 学习	
	1.1	**1.2**	**1.3**	**1.4**	**2.1**	**2.2**	**2.3**	**3.1**	**3.2**	**3.3**		**10.1**	**10.2**	**11.1**	**11.2**	**12.1**	**12.2**
大学化学	L				L												
数值计算方法	L																
应用文写作												L				M	
工程图学			H			M											L
工程力学		H			H												
电工电子学		H				M											
机械原理			H			H											
机械设计			H			M											
液压与气压传动			M			M											
测试传感技术			L			L											
机械制造技术			H			M											
电气控制与 PLC			M			M						M					M
流体机械基础				L													
泵站计算机监控技术				L													
水泵 CFD 技术与应用			L														
机电传动控制			L														
机电一体化系统设计				L													
机器人技术				L													
管理学/经济学														M			
传热学与流体力学基础		M				L											
工程材料及成型基础		M										L					
控制工程基础				M		M											
三维实体建模与设计																	H
单片机原理与接口技术			M														
文献信息检索												L					
大学物理实验																	
机械工程导论与认知实践												L					
零部件测绘及 CAD												L					
电工电子实习												M					
工程训练 I																	
工程训练 II																	
机械原理课程设计								M	H	M		M					
机械设计课程设计								M		H		H					
机械制造技术课程设计								M	M	M		M					
科技创新训练				H		H	H	H	M	M		H	H	H	H	H	
单片机/PLC 课程实训						M	M		M	M		M		H	M	M	M
专业综合实践				H		H	H	H	H	H		H		H	H	H	M
生产实习												M					
毕业实习												M					
毕业设计（论文）				H		H	H	H	H	H		H	H		H	H	H

人才培养方案优化情况说明：

2019 年对 2017 级的培养方案进行了优化，其中比较大的改动有：

1）将毕业学分由 180 学分调整为 165 学分；

2）将流体与水利机械、机械电子和机械制造三个专业方向调整为两个：流体与水利机械方向和机械电子；

3）增加了交叉学科课程选修要求（至少 3 学分）；

4）将实践课学分比例由 36.4%提高到 40.0%；

5）增加了科技创新训练 2 学分；

6）并制定了归属同一学科的辅修专业的专业课程等等。

另外，对培养方案配套的课程大纲也进行了修订，优化了课程目标和毕业要求的对应关系、以及课程目标达成度的评价标准。

（3）人才培养目标达成度测评认证情况

本专业于 2019 年 4 月成立工程教育专业认证工作组，并在 2020-2021 年期间对 2021 届毕业生进行了毕业要求达成性评价。部分核心课程各毕业要求指标点的达成情况如表 4 所示。**2021 年 10 月，本专业已经正式向教育部提出工程教育专业认证申请。**

表 4 专业部分核心课程毕业要求指标点的达成情况

序号	课程名称	毕业要求指标点	课程目标	考核内容	达成度分值
1	机械制图及 CAD1、2	1.3 2.2 5.2 12.2	1 2 3 4	详见《机械制图及CAD》大纲	0.827
2	机械工程力学 1、2	1.2 2.1	1 2 3	详见《机械工程力学》大纲	0.710
3	互换性与技术测量	2.1 4.1 4.2 4.3	1 2 3 4	详见《互换性与技术测量》大纲	0.694
4	控制工程基础	1.4 2.2	1 2 3 4 5 6	详见《控制工程基础》大纲	0.798
5	电气控制与 PLC	1.3 2.2 5.2 9.1 9.2 10.1 12.2	1 2 3 4 5 6 7	详见《电气控制与PLC》大纲	0.772
6	机械制造技术	1.3 2.2 4.1 4.2 4.3	1 2 3 4 5	详见《机械制造技术》大纲	0.761
7	机械设计课程设计	3.1 3.3 5.2 6.2 7.2 8.3 10.1	1 2 3 4 5 6	详见《机械设计课程设计》大纲	0.812

2. 积极推进培养模式、教学团队、课程建设、课程思政、教材出版、教学模式、教学管理等专业发展重要环节的综合改革

（1）适应社会需求，深化SWH-CDIO-E人才培养模式改革

为进一步贯彻《教育部财政部关于“十三五”期间实施“高等学校本科教学质量与教学改革工程”的意见》文件精神，切实推进学校教学改革，着力提高教育教学质量，结合浙江水利水电学院“十三五”专业建设发展规划的实施，借鉴国际工程教育改革的最新成果 CDIO 工程教育理念与模式，全面推进本专业应用型人才培养模式改革与实践。结合现有的“3+1”型 SWH-CDIO-E 人才培养模式，以《全国工程教育专业认证标准》和国家专业质量标准为指南，重构专业人才培养方案。按照专业认证七个方面的通用标准和机械类专业三个补充标准要求，搭建专业人才培养软硬件平台，落实“成果导向，学生中心，持续改进”的三大工程教育认证基本理念，着重培养学生的工程意识和工程能力，以及创新创业能力，为社会培

养高素质应用技术型人才。

1）总体思路

以培养工程意识强的一线机械工程师为目标，坚持人才培养模式改革的探索，重视能力培养，强化工程素质训练，形成以机械制造业为对象，以机械工程实验教学中心为支撑，以相应管理机制和制度为保障的育人环境和校园文化；积极主动地与地方企业合作，在人才培养、专业和课程建设以及产学研合作等方面取得显著的成效，逐步形成鲜明的特色，并产生良好的社会效果。

2）具体改革措施

① 以 SWH-CDIO-E 人才培养模式为主要研究对象开展相关教育教学改革研究。

以浙江省高等教育“十三五”第一批教学改革研究项目“工程教育认证背景下机自专业应用型人才培养的研究与实践”和校教育教学改革项目“基于 SWH-CDIO 理念的机自专业创新型人才培养模式研究与实践”为突破口，建立以 CDIO 和 OBE 为指导思想的培养模式，将产品、过程和系统生命周期的开发与运用（构思、设计、实施、运行）作为工程教育的背景环境，以项目设计、实施为导向，以工程能力培养为目标，精心规划一系列适用于不同教学阶段的项目。在教学活动中，将学生需要掌握和学习的内容与项目设计和实施有机联系、紧密结合。通过设计和实施过程，学生学以致用，从而达到能力培养和综合发展的目的。具体包括：通过教师、学生、校友和行业企业专家调研，形成专业调研报告，建立和完善专业人才培养目标体系，明确专业毕业生所需获得的知识、技能和态度等方面的要求；结合本专业细化各项指标，制订专业 SWH-CDIO-E 能力大纲，并开展全程能力测评认证工作。

② 以创新型人才培养为目标开展相关的课题研究。

通过开展“一班一室一团一赛一项目”创新活动（即机械创新班、机械创新工作室、学术社团、学科技能竞赛、科技创新项目），构建校院两级实践创新训练环境，实现课内外有机融合，以课外促进课内，让学有余力学生接受创造发明探索性教育，激发学生学习兴趣，提高学生的专业硬能力和专业软能力，突出人才培养“创新机械”的特征

③ 以提高课堂教学效果为出发点，开展“项目+作品+竞赛”课程教学模式研究。

以工程项目为载体，搭建通用核心能力、工程基础能力、专业基本能力和专业综合能力“四大能力平台”，构建“基础、提高、综合、创新”多层递进式实践教学体系，创新“目标导向、项目引领、任务驱动、理实融合、结果评价、持续改进”的六位一体项目制课程教学模式和企业全程参与的“产品设计制作月”特色综合实践项目。依托学校行业办学优势，创立企业学院，深化校企合作，拓宽项目来源。将工程项目融入课程教学、学科竞赛、科创项目和毕业实践，通过项目构思、设计、实现、运作，强化学生实践能力训练，提高学生的实践动手能力和创新能力。

（2）通过内引外培，强化双师双能教师培养与课程团队建设

要想培养出合格的应用技术型本科专业人才，首先专业任课教师必须具备先进技术应用能力。与一般本科院校相比，应用技术型高校的教师应具有较长时间的企业实践工作经验，能够带领学生做企业真实项目，帮助企业解决实际问题。本专业师资建设的主要举措是：1）从企业引进具有工作经验的博士或高级技术人才，充实教师队伍；2）对从高校引进的应届博士，要求参加半年以上的带项目脱产工程锻炼，以弥补实践工作经验的不足；通过导师制培养、参加培训、教学观摩、实验室设备操作、下企业锻炼等方式，使其尽快掌握教育教学方法，适应本科课程教学、具备从事科研和科技开发工作的能力；3）对原有的教师，则通过参加访工、访学、培训、下企业、下实验室等方式，锻炼自身的工程技术应用能力，提高自身胜任应用技术型本科高校课程教学的能力。

通过四年的建设，本专业现有专业任课教师 28 人，其中教授 3 人，副教授/高级工程师/副研究员 8 人，硕导 4 人，高级职称占比 39.3%；博士研究生 16 人（含在读 3 人），占专业教师比为 57.1%；研究生学历教师占专业教师比为 94.4%。专业教师中获省优秀教师 1 人，全国水利职教教学新星 2 人，省中青年专业带头人 3 人，浙江省“151”人才 3 人，省级一流课程负责人 3 人。近四年来，本专业教师积极开展教科研工作，研究成果获批校级教学成果奖 1 项，申报省级教学成果 1 项。主持各类科研项目 20 余项，其中国家级 2 项，省级研究项目 10 项。发表科研论文 82 篇，其中核心期刊及三大检索论文 33 篇。取得专利和软件著作权登记 120 余项，其中发明专利 26 项。

根据机械类本科专业的课程类型和课程特色，本专业组建了《机械制图与 CAD》、《机

械原理与机械设计》、《液压与气动》、《机械制造技术》、《电工电子技术》、《单片机原理与接口技术》、《电气控制与 PLC》、《CAD/CAM 技术》、《数控技术》、《水利机械》等 10 个由专业带头人、骨干教师、企业工程技术人员共同组成的课程教学团队，发挥团队优势。

（3）推进理实融合课程建设，提高课堂教学效果

应用技术型本科人才培养，其核心在于课程建设与课堂教学。应用技术型本科高校的课程教学应体现理论与实践相结合，理论为实践所用，实践为理论做支撑，强调理实融合。应用型本科高校的课程教学内容安排，应既要有一定的理论深度，充分考虑到学生后续的发展，还需要有较多的实践环节，以提高学生的实践动手能力。因此，本专业的课程建设思路是继续推行“项目+作品+竞赛”课程教学模式，以实际工程项目为载体，重构专业课程体系，重构课程教学内容，积极开展项目制教学，让学生在做中学、学中做。同时通过合作模式，校企共同编写项目化教材，使之适应应用型人才培养的需要。目前已经建成《电气控制与PLC》、《工程制图》、《三维实体建模与设计》等省级一流课程 3 门。

（4）全力推进课程“思政十法”，思政育人“润无声”

根据高等学校课程思政建设指导纲要教高〔2020〕3 号，以及《浙江省教育厅办公室关于开展高校课程思政教学项目建设工作的通知》（浙教办函〔2021〕73 号）的文件精神，要在课程教学中把马克思主义立场观点方法的教育与科学精神的培养结合起来，提高学生正确认识问题、分析问题和解决问题的能力。要注重强化学生工程伦理教育，培养学生精益求精的大国工匠精神，激发学生科技报国的家国情怀和使命担当。一方面，学校积极开展课程思政教学名师和团队遴选，推出一批课程思政示范课程、设立一批课程思政建设研究项目；另一方面，要求每位授课老师要挖掘所授课程的思政元素，把德育元素浸润式地“无痕融入”课程教学，寓价值观引导于知识传授和能力培养之中，以引起学生的情感共鸣、触动灵魂、激发思维，从而内化为学生的个人涵养和整体素质，为学生塑造正确的世界观、人生观和价值观赋能。目前已经立项省级思政项目 1 项，校级课程思政项目 2 项，校级核心素养课程 1 门，课程思政研究论文获省级特等奖 1 项。

（5）集中优势力量，稳步推进教材建设

根据教育部关于“十二五”普通高等教育本科教材建设的若干意见(教高【2011】5 号）文件，以及浙江省教育厅《关于加快推进普通高校“互联网+教学”的指导意见》（浙教高教〔2018〕102 号）的精神，本专业鼓励教师编写、出版、选用适合本校教学的项目化教材，并积极推进学校与行业合作编写的实践教材，全面提升本科教材质量，充分发挥教材在提高人才培养质量中的基础性作用，培养应用型本科高级应用型人才。目前已出版专业教材与专著 4 部，其中《三维实体建模与设计》课程教材入选浙江省普通高校“十三五”第二批新形态教材建设项目。

（6）教学管理模式创新，形式多样

学校高度重视教学质量的管理，制定了一系列教学管理制度《浙江水利水电学院校院两级教学督导工作条例》、《浙江水利水电学院校院两级教学评估工作条例》、《浙江水利水电学院本科学生学籍管理规定》等，并逐步建立规范、全面、科学的教学质量监控体系，对教学质量实施检查、评价和反馈，并对反馈结果进行分析改进，加强专业教学规范管理。作为二级学院，严格按照学校的教学文件要求进行执行，并根据学院和专业的自身情况编写了《机械学院教学规范化文件汇编》，出台了包括课堂教学、课程设计、实习实训、毕业设计等 59 个教学管理制度，保证了本科教学的正常运行。

1）实行专业负责人与教研室主任协同负责专业建设机制

学校出台专业负责人与教研室主任聘用机制，明确了专业负责人与教研室主任的职责、义务与权利，双方共同对专业建设的质量负责。

2）教学工作评价激励机制和约束机制相结合

学院定期开展“魅力一课”、“优课优酬”、“青年教师教学技能竞赛”等教学活动，提高教师从事教学的积极性，并努力提升教学质量。教师教学质量的评价采用校院两级评估体系，教学评价成绩由学生评教成绩、同行评价成绩和督导评价成绩三部分组成。学生评教由学院教学质量评估小组在对学生进行宣传和发动的基础上，组织学生集中填写，此外，教学信息员及时反馈教师在教学过程中存在的问题与不足，以及学生在学习过程中存在的困难等。反馈的意见由教学质量管理科整理汇总，定期反馈给学院，并督促整改，促进教师改进

教学工作，提高教学质量。教师课程评教结果与教师晋职、聘任、教学津贴考核奖发放、年终考核奖发放挂钩。

3）严格考试管理制度

认真组织落实《浙江水利水电学院考试管理条例》，教师命题必须符合课程教学大纲和考试大纲的要求。学生的课程成绩，按照教学大纲要求由知识分、技能分、态度分三项组成，由任课教师严格把关，教研室主任审核。任课教师在考试结束后应及时登记成绩，并填写试卷卷面分析和命题情况分析，将考试材料按规定时间送交存档。学院采用教师交叉审核方式，对教师提交的试卷资料进行检查，以保证试卷评阅的公平、公正、公开。

为了更好地推进工程教育认证进程，学院还出台了《专业认证工作实施办法》、《各本科专业毕业要求达成情况实施细则》、《各专业的课程体系合理性评价实施细则》等和工程教育认证配套的文件 7 个，确保工程教育认证工作的顺利进行。

（7）强化过程监控，保障人才培养质量

人才培养目标与培养标准是否达到预期目标，需要有一个评估与评价过程。本专业初步构建了“两循环、三层面、五内容、六主体”的教学评价与评估体系，强化过程监控和结果导向。对照专业培养目标与培养标准，实施“学习产出”达成度测评。“两循环”指的是校内循环与校外循环，校内循环主要针对课程层面，校外循环主要针对专业层面。“三层面”指的是项目、课程、专业三个层面的评估与评价；“五内容”指的是评价的内容包括了专业培养目标、课程体系、教学内容、教学方法、教学评价等五个方面。“六主体”指的是通过教师、在校生、应届毕业生、校友、用人单位、以及第三方调查，建立反馈与社会评价体系，以此保证人才培养质量。

1）实行两级督导制，加强教学质量的监控力度

学校实行两级督导制，聘请教学管理经验丰富的教师担任学校和学院的教学督导员。两级督导组成员开展不定期推门听课，定期开展授课计划、试卷、实验实训等环节检查，并及时将检查结果情况反馈给学院领导和相关教师。同时教学督导组开展教学巡视制度，每周安排人员进行教学巡视，检查学生迟到早退旷课现象，发现问题及时解决。定期组织学生评教及教学情况调查等各项活动；检查各项教学管理制度的执行情况，杜绝教学事故和教学差错事件的发生，每学期末完成工作总结；协助学院抓好教风、学风，确保教学工作正常有序地进行，促进教学质量不断提高。

2）建立定期师生座谈与毕业生走访调查机制

每个学期学院均要组织一次期中师生座谈会，听取学生对教师教学的意见或建议；每年学生毕业前，专业教研室均组织一次毕业生座谈会，发放调查问卷，听取学生对专业建设的意见和建议。每年学院均会组织一次毕业生走访调研，听取用人单位对毕业生的评价及后续人才培养意见等。

3）严格毕业设计管理，提高毕业生质量

为了加强本科专业毕业设计管理，学校出台了校级规范要求：浙水院本科毕业设计（论文）工作管理办法（浙水院【2015】158 号）；关于印发百篇（件）优秀毕业论文（设计）和优秀指导教师奖评选办法的通知（浙水院【2015】167 号）。根据学校的安排，学院出台了“机械与汽车工程学院机自本科专业毕业设计（论文）实施细则与工作计划”。

学校教务处负责制订全校毕业设计（论文）的有关条例与实施意见；了解与检查各专业毕业设计（论文）工作实施情况，组织专家对各学院毕业设计（论文）整个工作的质量进行评价，并做好毕业设计（论文）质量的分析总结工作。

机械学院毕业设计（论文）工作领导小组负责制订本院工作计划；组织命题、审题、选题与开题；落实指导教师；检查监督；组织答辩；评定成绩；进行毕业设计（论文）质量分析与总结和推荐优秀毕业设计（论文）等工作。

机械学院确保能够按照毕业设计时间节点做好毕业设计（论文）的总结工作，总结的内容计划包括：毕业设计（论文）基本情况（包括英文翻译情况、任务书完成情况、开题情况、指导情况、过程检查情况、成果、成绩评定等），本单位毕业设计（论文）工作存在的主要问题，本单位提高毕业设计（论文）质量有显著效果的做法，对毕业设计（论文）工作的意见和建议等。

机械学院制定了毕业设计（论文）资料归档管理工作的规定，每生上交的材料包括：（1）毕业设计（论文）及相关图纸、软硬件成果等；（2）相关材料（内含毕业设计（论文）任

务书、开题报告、文献综述、外文资料译文及原文、指导记录、中期检查表、实物验收单、答辩资格审查表、答辩记录）；（3）评审表。资料由学院统一保存。

另外，学校为了方便学生管理，开发了本科毕业设计管理平台，方便师生间沟通和各种材料的上交审阅、归档等。

3．校内外实践条件建设与实践教学管理

（1）按照人才培养方案的要求，建设专业实验室

校内外实践条件的建设，直接关系到人才培养的质量。为了培养合格的应用技术型人才，本专业校内实验室建设重点考虑以下几点：1）满足人才培养方案中所规定的课程教学的需要，并根据教学内容的调整，及时更新仪器设备；2）采用理实一体化模式建设实验场所，既是实验室，又是教室，融教学做于一体；3）新实验设备采购以实用性为主，能够满足设计性、综合性、创新性实验的教学需要；4）体现学院专业的办学特色，重点建设泵、阀、闸等水利机械实验室、水下检测机器人实验室等；5）在实验室管理方面，探索多种样式的开放式实验室管理模式，以丰富学生的业余生活，提高学生的实践动手能力、自我管理能力、创新能力等。

本专业实验室隶属于机械工程省级实验教学示范中心，包括了机械基础实验室、先进制造技术实验室、机电工程实验室、机械自动化综合实验室、泵站综合性能测试实验室等 5 个实验室。其中先进制造技术实验室为中央财政与省财政重点资助实验室，机械基础实验室、机电工程实验室、机械自动化综合实验室为省财政资助实验室，泵站综合性能测试实验室为水利厅专项经费资助实验室。目前专业实验设备总值 1900 多万元，实验室现占地面积超过 $5000m^2$，满足机械工程学科专业发展的需要。

另外，为了提升教师和学生的科研水平和创新能力，近几年学院依托机械工程省一流学科、先进水利装备省级工程研究中心、浙江省农村水利水电资源配置与调控关键技术重点实验室、中国-白俄罗斯水利水电安全监测智能化装备与系统“一带一路”联合实验室等省部级平台，建有激光熔覆等 10 多个科研实验室。

（2）加强校企合作，积极推进产教融合

本专业历来重视校外实习基地的建设，通过加大产学研基地建设力度，使人才培养、科学研究、科技合作、成果转化、技术服务等与地方行业企业有机结合，实现真正意义上的互惠互利、共同发展。

校外实践教学条件的建设，则主要以紧密型校企合作基地建设为主，按照学校提出的“八个共同”校外实践基地建设方针，融产学研于一体，真正发挥校企合作企业的作用。目前本专业现有校外实习基地 30 余家，其中紧密性合作基地有 5 家，并与泰瑞机器股份有限公司合作共建“泰瑞企业学院”。

通过校企合作，平台的建设将本着创新资源配置更优、联合创新能力更强、开放服务水平更高、具有良性自我发展机制的建设原则，探索以高校为主体、企业紧密协作的产学研协同创新服务体系，着力解决中小企业共性需求，畅通信息渠道，改善经营管理，促进转型升级，提高发展质量，增强市场竞争力，进一步推进我校的区域协同创新工作的同时，激发地方企业参与人才培养的热情，为本专业校外实践基地的建设创建了良好的条件，最终实现互惠共赢。

（3）加强实践教学管理，提高人才培养质量

1）保证实验开出率。为了能有效培养学生的实践能力、创新能力和工程意识，提高学生的综合应用能力，在培养方案中加大了实践教学环节的分量，结合大学生科技竞赛，鼓励学生开展形式多样的开放式、综合性实验和创新性实验活动，以提高学生动手能力，培养学生的创新能力。

在本专业的实验课程设置上，共开设了《工程力学》、《电工电子学》、《机械原理》、《机械设计》、《液压与气压传动》、《测试技术》、《机械制造技术》等 11 门含有实验的课程，累计课内实验学时达 62 学时，专业课程实验开出率达 100%。

对于学科基础类的大学物理课程，独立开设了 2 周共 56 学时的《大学物理实验》等开放式、综合性实验、创新性实验教学项目，学生通过这些综合性实验项目的训练，一方面提高了综合应用所学知识解决实际问题的能力，另一方面也开阔了视野，了解本专业前瞻性知识。

在实验教学模式上，从单一的验证理论和培养学生动手能力上延伸到加强对学生思维能

力和创新能力的培养上；既重视实验教学对理论的验证功能，又重视实验教学对理论的补充、深化和发展作用；在统一要求与个性发展的关系上，继承“预习—讲解—实验—报告”的传统教学模式，同时因材施教，重视学生在教学活动中的主体作用，重视发挥学生的主动性和创新能力。

在实验教学档案管理方面，为保证实践环节教学大纲及指导书规范、齐全，学院严格按规章制度制定实践教学大纲、教学计划、实验计划。本专业的实验教学大纲、实习大纲、实践教学指导书的完备率达到了 100%。各门课程的实际教学进度均和授课计划相符，并具有完备的实践教学执行情况统计资料。

2）提高综合性、设计性实验的比例

实践教学是本科教学中的重要环节，是培养学生动手能力、解决实际问题能力的重要手段，实验教学内容中的综合性、设计性实验则是培养学生专业共和素质、创新能力和重要手段。

为培养学生实验技能、综合分析能力、实验动手能力、数据处理和查阅资料能力，专业教学计划中的实验课程大多数都设置了综合性、设计性实验内容。综合性实验具备以下特征：实验内容的复合性、实验方法的多元性和实验手段的多样性。而设计性实验需要学生根据指定的实验目的和实验条件，自行设计实验方案、选择或制作仪器并加以实现，目的在于激发学生学习的主动性和创新意识，培养学生独立思考、综合运用知识、提出问题和解决复杂问题的能力。

按照教学大纲和培养计划的要求，本专业设置有实验的课程共 11 门，其中具有综合性、设计性实验的课程为 9 门，占总实验课程的 81.8%，这也是目前稍显不足的地方，后期将通过调整实验项目设置和模式改革，提高综合性和设计性实验的比例。

本专业所编写的综合性实验课程教学大纲、实验指导书内容齐全，格式规范。对于综合性实验教学材料的收集、整理和存档工作，有专人负责，定期修订综合性实验课程教学大纲、实验指导书，相关实验日志、实验报告等各项文件内容完备，管理有序。

3）重视实习教学管理，提高学生的实践动手能力

实习是重要的实践教学环节，通过实习培养学生综合运用专业知识、分析解决实际问题能力，增强学生职业道德意识和社会责任感。

实习过程管理：实习过程管理严格，保障得力。本专业组织指导教师全面督查学生实习情况，通过实习单位走访、电话联系等多种通讯方式，及时与学生和实习单位进行沟通，了解每位学生的实习情况，帮助学生解决实习中遇到的问题，并督促学生迅速到岗，进入实习状态，全面督促和指导学生，管理规范严格。同时要求指导教师要按照进度要求指导学生撰写、上交实习报告，进行评价。目前，本专业的专业各项实习工作已经顺利完成。

4）实验室开放管理，为学生创新与自主学习提供平台

学院制定了实验室开放管理办法，从制度上保证了实验的开放。同时，通过组织学生进行包括浙江省大学生机械设计竞赛、浙江省“挑战杯”大学生课外学术科技作品竞赛，参与大学生创新创业训练计划项目、省新苗人才培养项目等内容丰富的学科竞赛活动，促进实验室的开放。

今后，将继续加大生均经费投入，切实提高教学经费使用效率。集中力量加强实验室建设投入，多渠道争取和筹措资金，保证本科实验教学 100%的开出率，体现实验室建设的前瞻性、先进性、适应性和开放性，使综合性、设计性、创新性实验所占比重逐年提高。同时，有计划地投入经费，保证专业图书资料、专业期刊、工具书、最新技术资料等建设。

4.学生科技活动与创新创业教育开展情况

（1）建立机械创新班，培养优秀拔尖人才

机械创新班的创建旨在贯彻落实党的“十八大”强调的“教育创新”精神，突出“发展个性”的办学特色，大力推进创新教育，弘扬浙江水利水电学院“动手实践”学风，以适应浙江水利水电学院作为应用型试点示范校“培养高素质应用型专门技术人才的本科院校”定位目标。

机械创新班主要致力于建设基于“终身教育”理念的大学生自主学习。本着“时间上要留有余地，空间上要有足够场所，机制上要有充分自由度”的原则，以“普及和提高相结合、过程和目标相结合”的方式，构建大学生创新学习模式。“普及”是指为全院本科生提供科技训练的各种机会，广泛开设创新实践类课程、开展作品设计与制作活动，参与机械设计竞

赛、机器人竞赛等学科技能竞赛，以及申报大学生创新创业项目大学生科技竞赛。“提高”是指提高学生工程技术应用能力、动手实践能力和创新能力，改变传统课堂教学以传授理论知识为主的局面，并采用导师制和项目制的教学方式，重点实现动手能力、创新能力以及分析问题、解决问题能力的培养。为优秀人才脱颖而出创造更多更好的机会。机创班自从 2015 年 9 月开始试点以来，已有近 300 名优秀学生进入“机械创新班”。大部分进入机创班的学生在学科技能竞赛、项目申报、学业学习等方面表现突出，成为专业的中坚力量。

（2）实施校省国三级学科技能竞赛体系，培育学生的实践动手能力和创新能力

近几年校内组织的竞赛有机械设计竞赛、机器人竞赛、机械 CAD 竞赛、挑战杯竞赛、创想杯、课外科技作品竞赛等，学生参与面逐步扩大，已达专业学生的 50%左右。校内竞赛获奖作品推荐参加省赛，乃至国赛。通过竞赛作品的调研、设计、材料选型与购买、加工制作、论文撰写、展示答辩等环节，学生的综合能力得到训练。

（3）积极配合学校做好创业精英班人才选送与培养

学校近两年开展了创业精英班的人才培养。机自专业作为首批升本专业，学生的能力培养基础扎实，竞赛作品多，创业前景较好，因此多人次被创业精英班选中，继续接受创业能力与创业意识的训练，为将来创业打下良好的基础。

四、建设成效

1.本专业于 2019 年 4 月成立工程教育专业认证工作组，并在 2020-2021 年期间对 2021 届毕业生进行了毕业要求达成性评价。**2021 年 10 月，本专业已经正式向教育部提出工程教育专业认证申请。**

2. 专业建设成效初步彰显。因办学特色明显，办学成效显著，专业所依托的先进水利装备技术中心 2019 年获批省工程技术研究中心。专业申请中白合作本科办学项目获得教育部审批通过，并于 2021 年开始招生。本专业教师近两年来立项省厅级教育教学改革项目和课堂教学改革项目 8 项，发表教改论文 4 篇，出版教材及专著 4 部，建成省级一流课程 3 门。

3. 人才培养质量显著提升。本专业近两年来平均就业率接近 93%，考研录取率平均为 20%。省教育评估院公布的毕业生调查数据显示：毕业生一年后的就业率、薪酬水平、就业满意度、创业率等均高于全省本科平均水平；企业对学生的实践动手能力、专业水平等评价均超过了 97 分，位居学校前列。在近两年，学生参加机械设计等学科技能竞赛，获国家级奖项 7 项、省级奖项 68 项，其中省级一等奖 11 项。立项国家级创新创业类项目 14 项，授权专利 14 项，软件著作权 15 项。学生获校十佳大学生、优良学分班比例远高于全校平均水平。优秀校友层出不穷，用人单位满意度高。

4. 教学改革示范效果明显。专业多项校内首创改革举措被多家应用型建设试点示范院校和我校其它学院学习并推广应用。如国内首创“产品设计与制作月”活动，入选学校星级校园文化品牌，受到了来校洽谈国际合作办学的白俄罗斯国立技术大学副校长 Yuri 教授的高度赞赏。校内首个开展“机械创新班”（2014 年开始）、“优课优酬”（2015 年开始）、“企业学院”（2016 年开始）等教改创新项目等，后推广至全校。

5. 教改成果广受社会好评。专业教学改革成果“地方行业院校水利机械‘一聚焦三突出’育人模式探索实践”获校级教学成果奖二等奖。多家媒体报道了专业的教学改革成果，如《中安在线》等报道了“机械创客空间”活动；《北方网》等报道了“项目+作品+竞赛”课程教学模式；《大江网》报道了“企业学院”校企合作新模式。《浙江教育报》报道了我校师生研发成功“两栖河长”机器人；《学习强国》平台报道了我院师生赴永康开展“工匠日里访工匠”课程思政活动。《浙江在线》报道了“产品设计与制作月”活动等。